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Bedload transport monitoring at the Albula mountain river

Dieter Rickenmann, Gilles Antoniazza

1. Introduction

In most hydropower plants, significant sediment transport from the upstream channel network is generally responsible for a progressive reduction of the useful reservoir volume, and sedimentation can threaten the safety of the infrastructures by potentially blocking the outlets. Faced with sediment overloading, the installations have to be purged regularly or sediment bypass structures have to be used, which represent economical losses. In this context, continuous bedload transport monitoring upstream of hydropower plants could provide a powerful and complementary management tool for (i) evaluating the yearly amount of sediment input into hydropower plants and (ii) for optimizing the management of sediment related operations, notably during flood events.

2. Method

As an indirect bedload transport measuring method, geophone sensors record the acoustic signals generated by bedload particles impacting on a steel plate. This method has already been applied successfully in many alpine streams. The main advantage of this indirect non-invasive method is to provide continuous records of bedload transport rate in both time and over a cross-section, while minimizing changes in flow conditions at the measuring site.

3. Study site

Since April 2015, a new bedload measuring station with geophone sensors is operational at the Albula River in Tiefencastel (canton of Grisons), upstream of the Solis power plant. The geophone sensors are fixed from underneath onto steel plates, which were installed at the riverbed flush with a new concrete sill in order to avoid sediment deposition over the sensors (Fig. 1). The construction of the new measuring station has been funded by the Federal Office for Environment (FOEN) and the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL).

Fig. 1: New geophone measuring station in the Albula River in Tiefencastel

At the nearby Solis hydropower reservoir, a sediment bypass tunnel was constructed in 2012, to avoid further excessive deposition of coarse sediments in the lake. At the bypass tunnel outlet, another geophone measuring station had been installed earlier. The combined observations of the two geophone measuring sites and regular survey of the deposits in the lake will allow calibrating the measuring systems and optimizing the management of sediment related operations, such as sediment flushing through the bypass tunnel during flood events.

4. Objectives

The objectives of the new measuring station at the Albula River can be summarized as follows:

- further development of bedload transport measurement with geophone sensors
- creation of a pilot station for bedload transport monitoring in a Swiss mountain river with an extreme annual rate of transport (around 80'000m^3/year)
- optimization of sediment management related operations at the Solis hydropower reservoir

5. First results of the bedload transport monitoring

The measuring cross-section is 15 m wide. Each second steel plate is equipped with a geophone sensor (15 sensors total), and also 8 acceleration sensors are installed. Data recorded during two months between mid-May and mid-June are presented in the figures below.

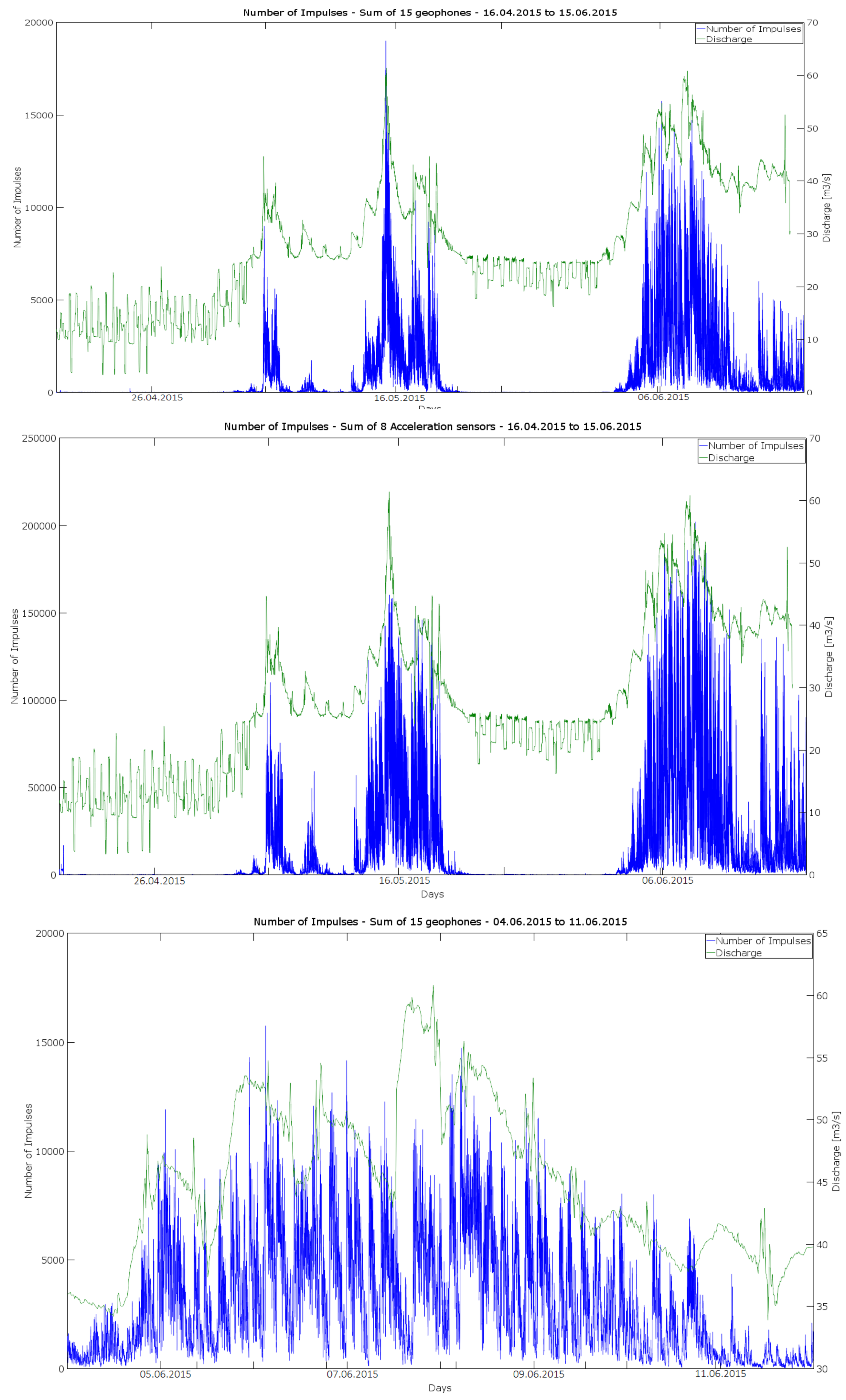

Fig. 2: Geophone sensor data for 2 months (top) and 8 days in June (bottom), and accelerometer sensor data for 2 months (middle).

6. Highlights

- A new pilot station with the Swiss plate geophone system is operational in the Albula River in Tiefencastel
- Discharges > 25m^3/s → daily cycles of bedload-transport fluctuations
- Continuous monitoring of bedload transport may help to support the sediment management at hydropower reservoirs or water intakes

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Energy Turnaround
National Research Programme NRP 70
e-dric.ch

HEPS4Power - Extended-range Hydro-meteorological Ensemble Predictions for Improved Hydropower Operations and Revenues

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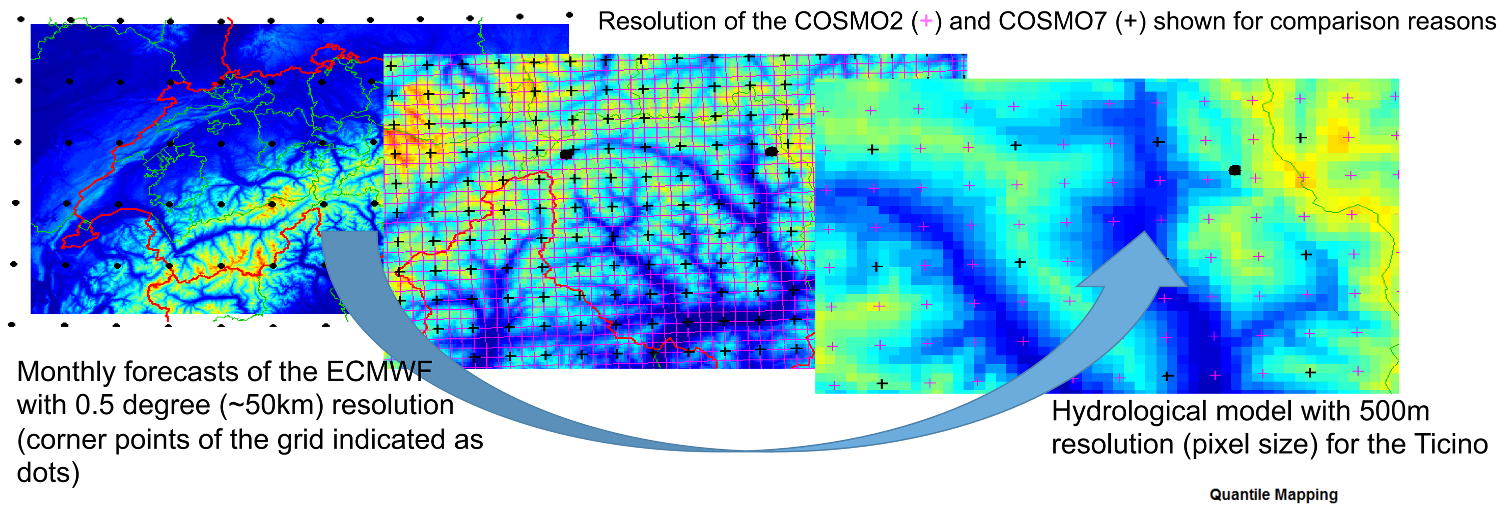
Abstract

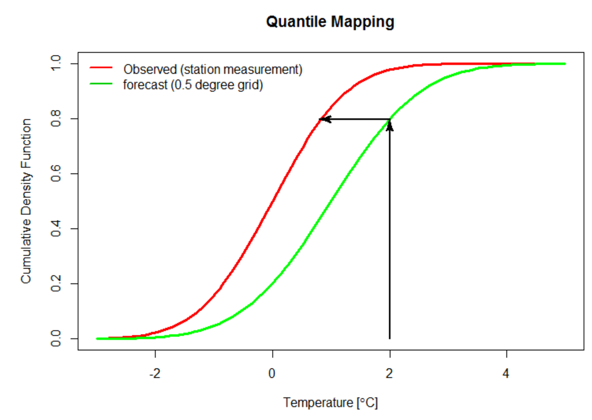
HEPS4POWER is part of the **NRP 70** funded by the **SNF** in order to demonstrate the potential of operational extended-range hydro-meteorological forecasts for fine tuning the production of energy from hydropower systems.
It is expected that the hydropower sector in particular might have considerable benefits from using **probabilistic hydro-meteorological forecasts** based on **Ensemble Prediction Systems** for the next 15 to 60 days in order to **optimize the operations and the revenues** from their watersheds, dams, captions, turbines and pumps.
The project team covers a specific system-oriented value chain starting from the collection and forecast of meteorological data (**MeteoSwiss**), leading to the operational application of state-of-the-art hydrological models (**WSL**) and terminating with the experience in data presentation and power production forecasts for end-users (**e-dric.ch**).

Scientific Questions

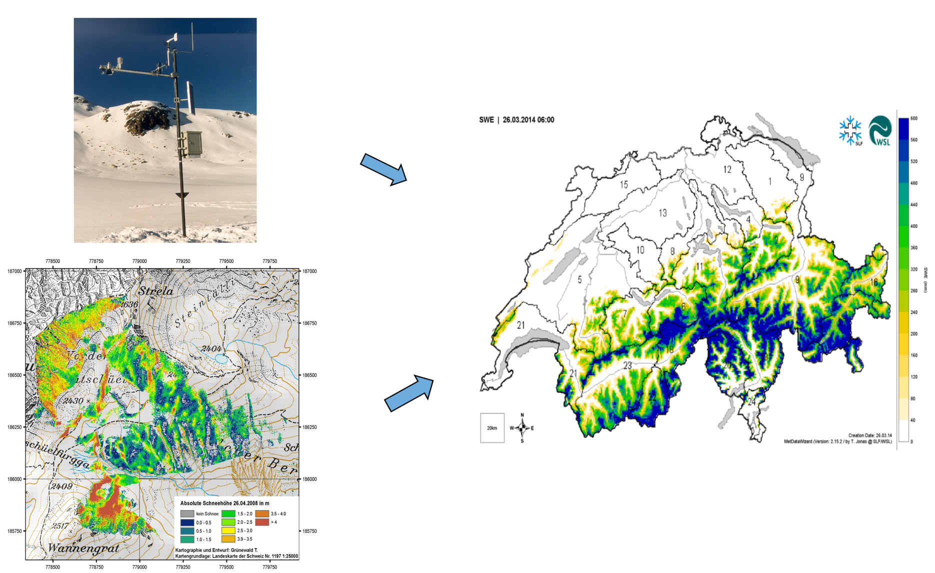
- Q1: What is the adequate **downscaling** procedure to obtain high value meteorological input for the **extended** Ensemble Prediction Systems?



In order to make global forecasts computed at a grid with ~ 50 km resolution applicable for hydrological models with high spatial resolution (e.g. 500m) in small mountainous catchments, different downscaling methodologies will be applied, e.g. Quantile Mapping.



- Q2: What is the added value **assimilating information** on snow-water equivalent and discharge in the context of monthly and seasonal discharge prediction?

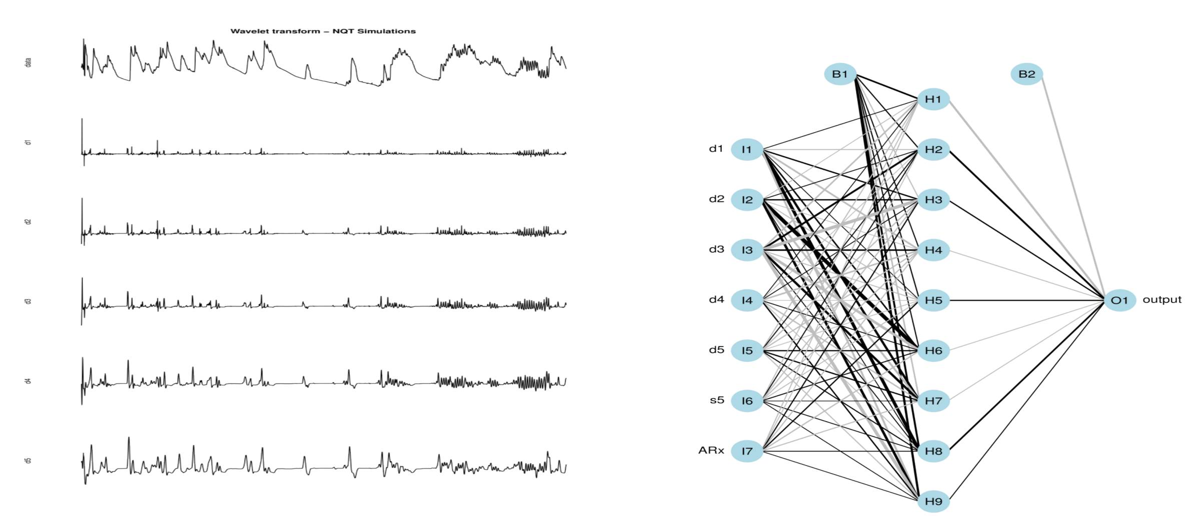


Hypothesis: Having the best information available regarding the actual situation of the snow at the end of the winter season will improve the forecast skill, e.g. for the inflow to reservoirs driven by melting water

- Q3: What is the added value of using a hydrological **multi-model** ensemble for hydrological predictions in **complex topographic areas**?

- Q4: Does extended-range and seasonal ensemble predictions contribute to improve the **revenues of hydropower systems**?

Additionally: Novel post-processing methods are developed at WSL in order to minimize the errors in the model simulations and the forecasts and for deriving the **Predictive Uncertainty** of the system (including measurements, model and forecast uncertainties).

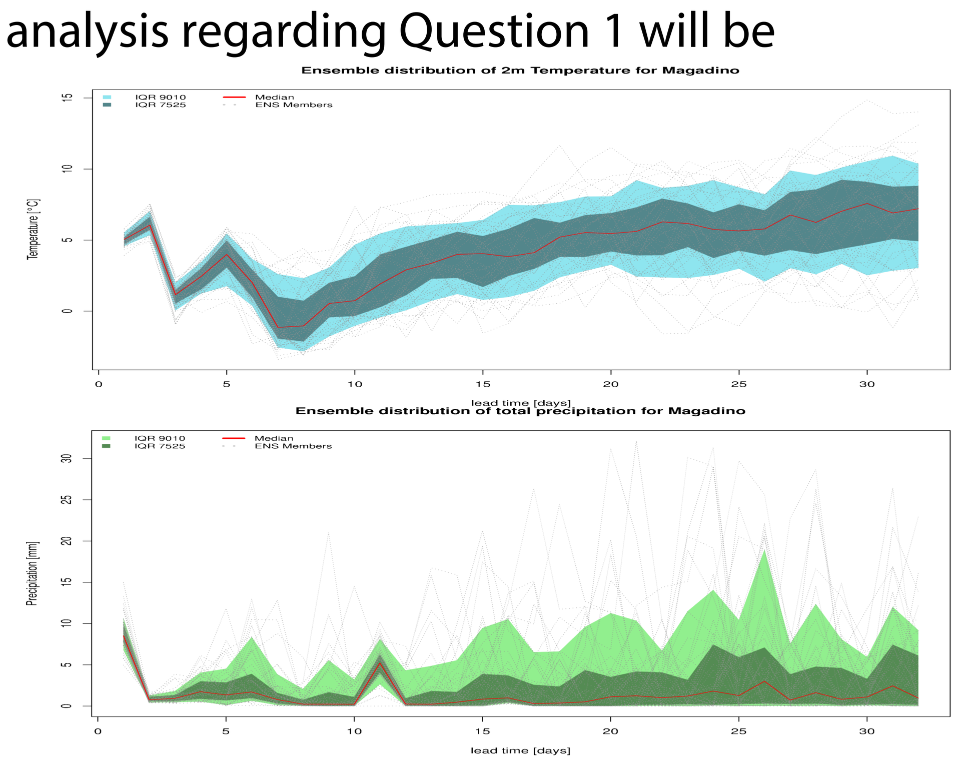


These methodologies combine Wavelet transformations, Neural Networks and Bayesian Uncertainty Processor

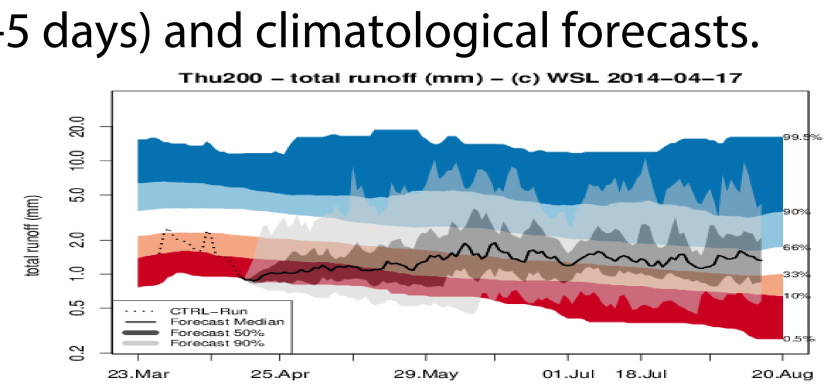
Concept

Step 1: MeteoSwiss (Q1) - data preparation and tailoring downscaling procedures for monthly to seasonal forecasts plus verifications. This is the topic of the first year and is ongoing at the moment. First results of the analysis regarding Question 1 will be published soon.

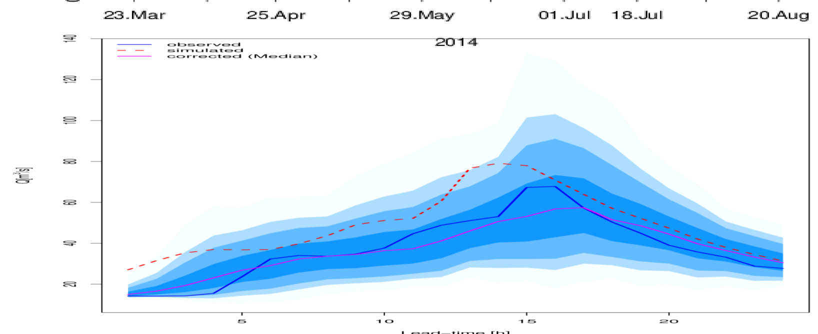
Example of monthly forecasts of temperature and precipitation produced by the Ensemble Prediction System at MeteoSwiss for a station in Ticino (based on the monthly forecast computed at ECMWF (UK))



Step 2: WSL (Q2, Q3) – taking the downscaled ensemble forecast data as input for the hydrological model PREVAH + other hydrological models and run multi-model simulations and forecasts (deterministic and probabilistic). Additionally the impact of snow maps will be analysed regarding the skill of the forecasts plus novel verification methods will be developed. These topics and the analysis of Question 2 and 3 will be the main focus of the project in 2016. Furthermore an additional advantage of the outcome of this project will be the possibility to fill the gap between already available short term forecasts (1-5 days) and climatological forecasts.

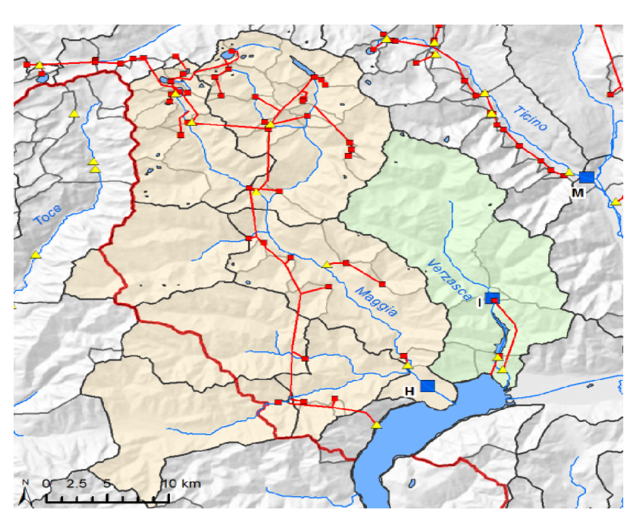


Long-term forecast run at the WSL (www.drought.ch) showing the possible evolution of the stream-flow at the Thur river based on climatology only (the monthly real-time forecasts are going to be implemented at next)



Predictive uncertainty of a 24 hour forecast for Zurich (Sihl) after running the post-processing methodologies developed at WSL

Step 3: e-dric (Q4) - integrating the probabilistic extended range forecast into a hydraulic model structure and derivation of decision rules for reservoir management plus verifications. This task and the analysis of Question 4 will be the last part of the project beginning 2017.



Example demonstrating the complexity of the hydraulic model structure of the model developed for the forecast of the hydro-power production in Ticino. The objective of the 3rd year will be the optimization of this power production running probabilistic extended range forecasts

Expected Results

Provide hydropower sector with valuable additional information for long-term decision making (abundance/scarcity/drought)
Possible benefits:
- Reliable predictions of inflows and exceedance probabilities
- Reduction of losses - Early indication of high risk periods (floods/ droughts) – e.g. Closing of captions in time to avoid obstructions by debris
- Preventive turbine operations
- Reduction of costs (reduction/minimization of spill-over)
- Long-term planning of maintenance of captions
- Coordination of the production from a network with different stakeholders

Related work:
Farinotti, D. et al., Towards decadal runoff predictions for high-alpine catchments
Anghileri, D. et al., Design of hydropower systems operation under current and future energy market conditions

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Towards decadal predictions for high-alpine catchments

Daniel Farinotti [1], Saskia Gindraux [1], Matthias Huss [2], Alberto Pistocchi [3], Christian Ginzler [1], Ruedi Bösch [1]

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1. Introduction

The research field of decadal predictions (or forecasts) is relatively new and has been declared as one of the "grand challenges" by the World Climate Research Programme. Targeting at a time horizon of up to 5-8 years, results are designed for a time frame relevant for most decision-making processes. The potential of this new generation of climate predictions in the hydro-glaciological context is hitherto unexplored, whilst glacier melt is important for many streams across Europe (Fig. 1)

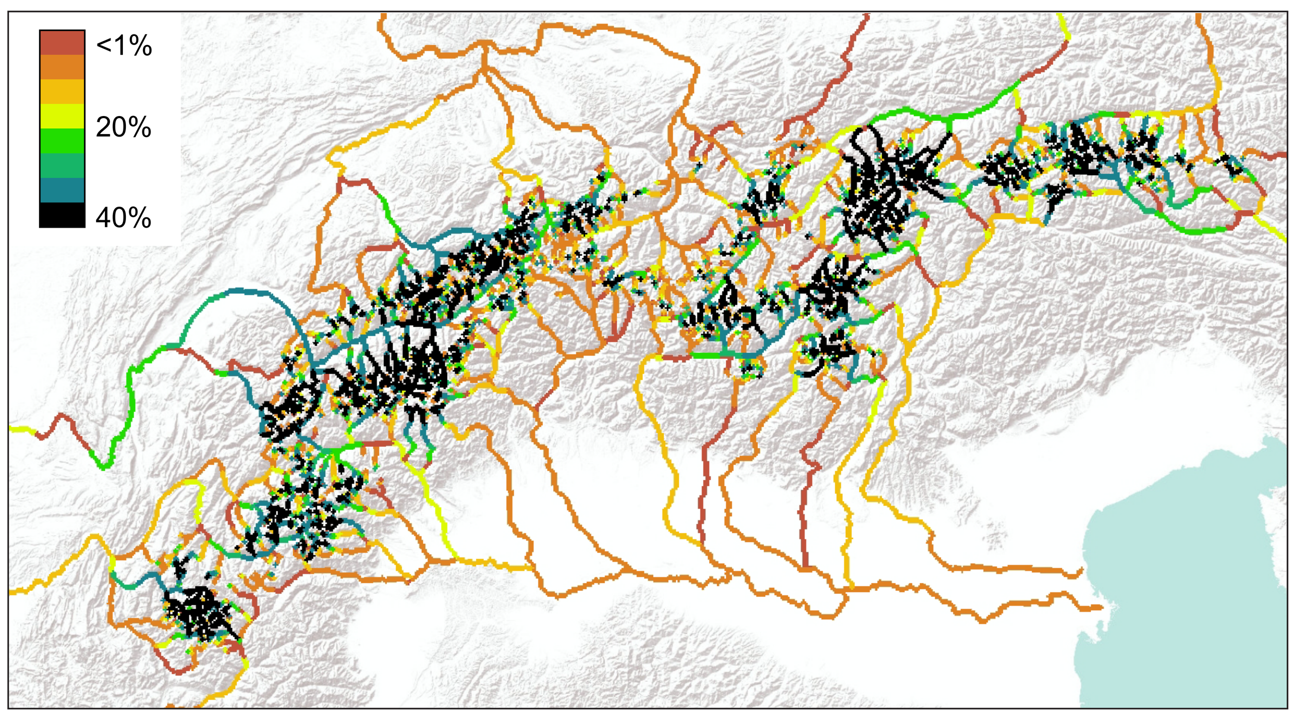

Fig. 1: Annual glacier runoff contribution across the European Alps. Glacier runoff is modelled with the approach by Huss&Hock (2015, doi: 10.3389/feart.2015.00054). Streamflow data are taken from the Global Runoff Data Centre (GRDC).

2. What are decadal predictions?

__Basic idea__: Use the information about the present state of phenomena with mid-term persistence to improve predictions otherwise based on external forcing only (Fig. 2).

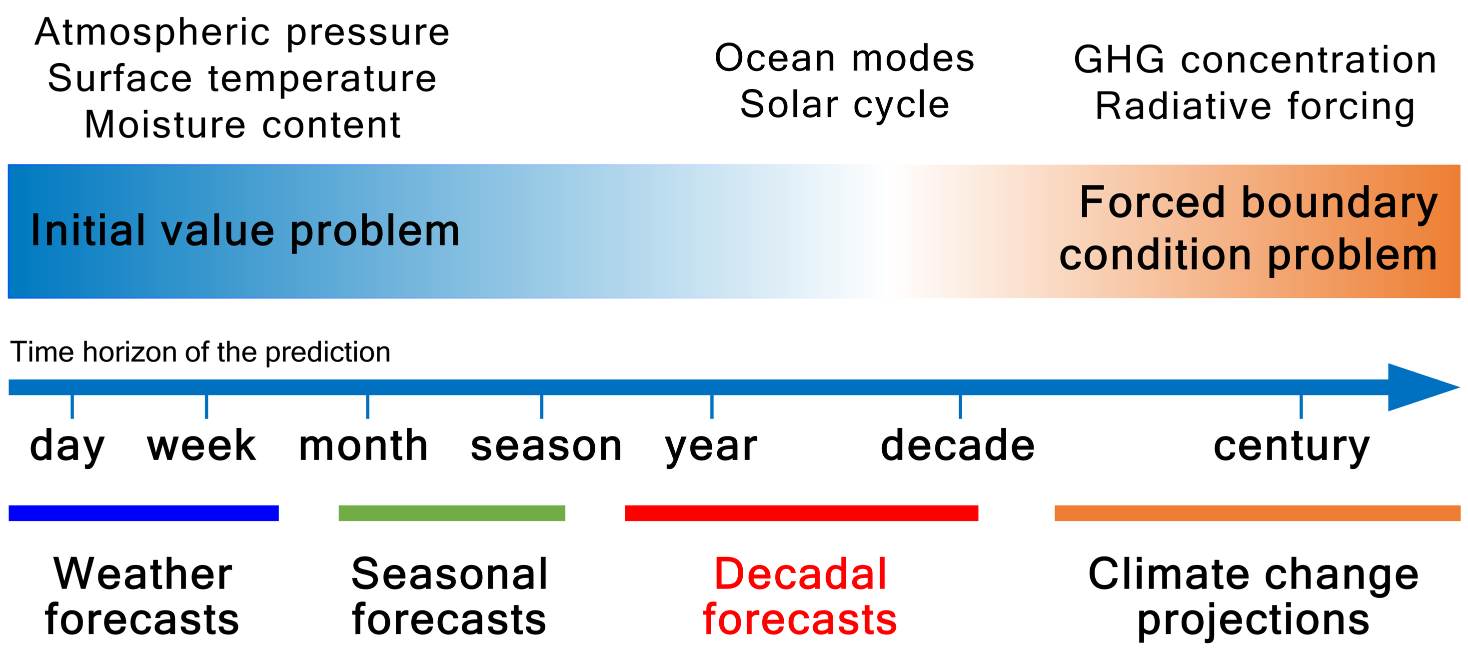

Fig. 2: Time horizon targeted by various forecasts / projections (bottom), including driving processes (top). Figure adapted from Meehl et al., BAMS, 2009, doi: 10.1175/2009BAMS2778.1

3. Why could it work for high-alpine cachments?

__Goal__: Provide decadal hydro-glaciological forecasts that are relevant for the planning of both hydropower operations and infrastructure.

__Starting point__: Atmospheric decadal forecasts currently available are more skilful in predicting temperature than precipitation.

__Working hypothesis__:
1) "Impact models" targeting regions that have processes controlled by temperature (glacier and snow melt or accumulation) can retain (some of) the skill of the atmospheric drivers.
2) Since cryospheric components have "inertia" themselves, better initial conditions (snow depths, ice flow velocity, ice thickness) should yield better forecasts as well.

4. General plan of action

Atmospheric forecasts
Temperature + precipitation
Monthly resolution; 10 year period
Initialization every 5 yrs (1961; 2006)
17 different GCMs, up to 10 members

Additional inital conditions
DEM of the surface
Snow depth distribution
Glacier ice flow velocities
Various data sources (Sec. 5)

→

Impact models
Hydrological model (GERM, PREVAH, ...)
Glaciological model (ice flow)

↓

Hydro-glaciological forecasts
Discharge + glacier geometry
Decadal time horizon

5. Where to get the initial conditions from?

A) Operationally repeated, Nation-wide air-borne surveys

- Conducted in the framework of the Swiss National Forest Inventory
- Providing glacier surface geometry and short-term changes (Fig. 3)

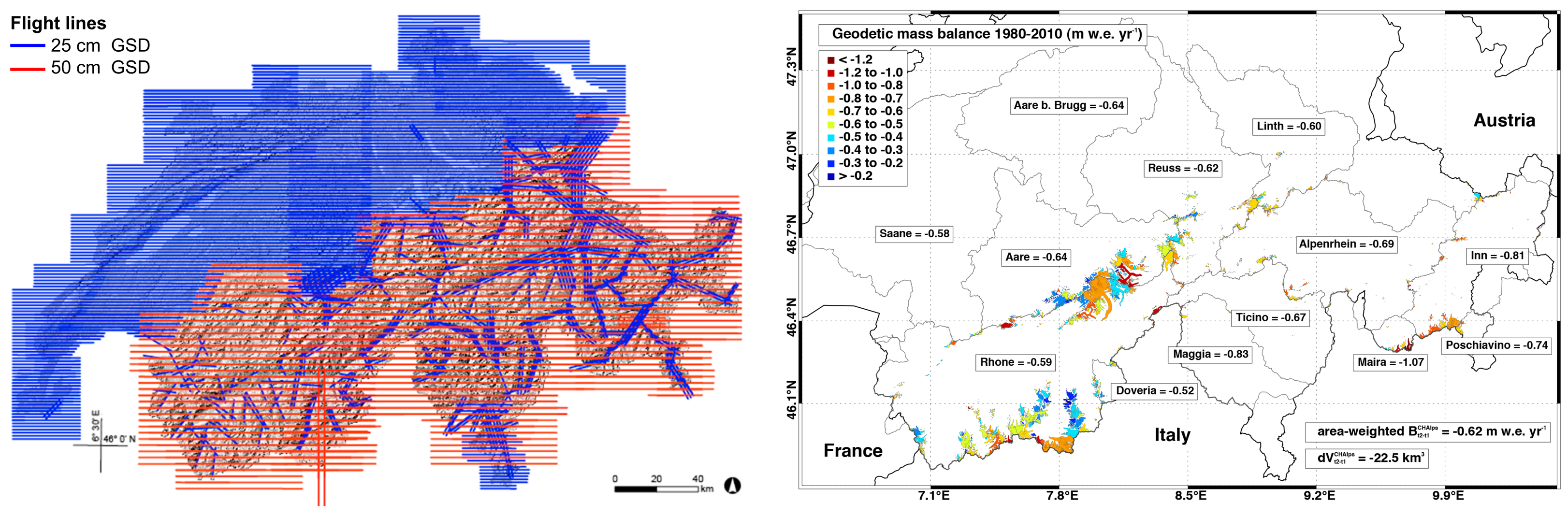

Fig. 3: Flight lines for the acquisition of ADS40/ADS80 images over entire of Switzerland (left). Operationally repeated surveys as planned (repeat cycle of about 3 years) open the possibility for short-term glacier monitoring, that can in turn be used for model optimization. The example on the right refers to the longer-term period 1980-2010.
Left figure adapted from Ginzler and Hobi, RS, 2015, doi:10.3390/rs70404343.
Right figure from Fischer et al., TC, 2015, doi: 10.5194/tc-9-525-2015.

B) Application of UAV photogrammetry

- UAV = Unmanned Aerial Vehicle (currently using SenseFly eBee)
- Application of Structure from Motion techniques
- Providing high-resolution DEMs and orthorectified photos on demand
- Used to extract information about snow height, ice flow velocity, and surface mass balance (under investigation)

Properties	RE camera	RGB camera
Model	Canon PowerShot S110	Canon IXUS 127 HS
Resolution	4048 x 3048	4608 x 3456
Focal Length	5.2 mm	4.3 mm
Pixel Size	1.86 x 1.86 µm	1.34 x 1.34 µm

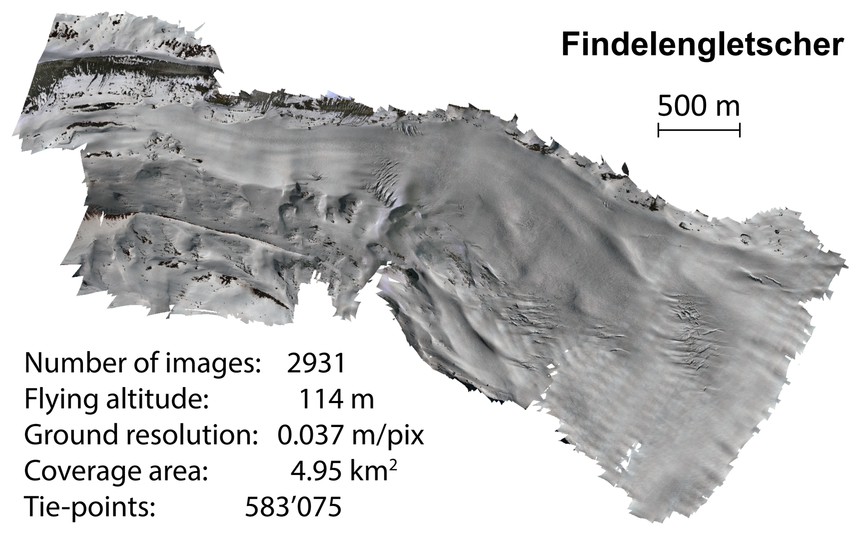

Fig. 4: Camera characteristics (table) for the UAV-system used (pictures: UAV and ground control point (left) and launching procedure (right)). An example of an orthophoto acquired for Findelengletscher in April 2015 (right) is shown. The mosaic is composed out of 10 flights.

6. And the atmospheric forecasts?

- Relying on CMIP 5 results (see Chap. 11 in IPCC AR5, WG1)
- "historical" (un-initialized) vs "decadal" (initialized) predictions
- Experimental forecasts from IC3, Barcelona, Spain (F. Doblas-Reyes)

7. Additional explorative analyses

- Automatized topographical exploration of locations becoming ice free, with the target of detecting potential artificial retention volumes.
- More than 200 sites with potential dam volume >0.1 km^3 (1km^2 x 100m) across the European Alps.
- Criteria regarding, e.g., geology, ecological impact, cost effectiveness, production potential, etc. not yet considered

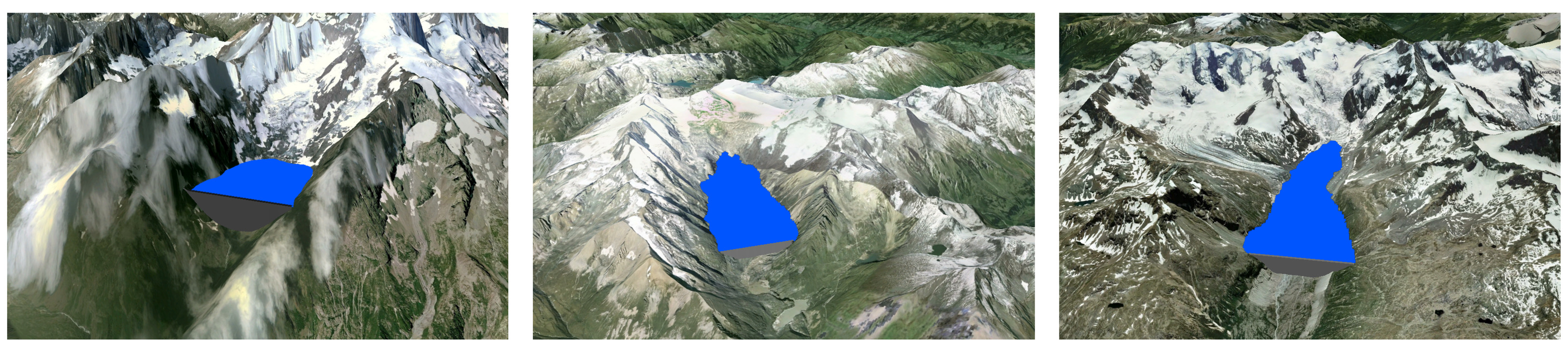

Fig. 5: Example for three detected sites: La Meije, France (left, 0.33 km^3 volume), Pasterze, Austria (middle, 1.05 km^3 volume), and Morteratsch, Switzerland (right,0.14 km^3 volume). The locations do not (yet) consider any criteria linked to, e.g. geology, ecological impact, cost effectiveness.

8. Outlook

- Skill assessment for the decadal hydro-glaciological forecasts
- Operationalization of the forecasting tool
- Accuracy assessment of the UAV-applications
- Selection of cases of particular interest in the explorative analyses

Related works

- Anghileri et al., Design of hydropower systems operation under current and future energy market conditions.
- Bogner et al., HEPS4Power - Extended-range Hydrometeorological Ensemble PredictionS for improved hydropower operations and revenues.
- Delaney et al., Potential for future hydropower plants in Switzerland: a systematic analysis in the periglacial environment.
- Peleg et al., Generation of very high resolution scenarios to investigate climate change impact on hydropower operation.
- Rabenstein et al., Swiss glacier ice volume using helicopter radar.
- Schaefli et al., Importance of glaciers for Swiss hydropower.

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Swiss Glacier Ice Volume
using Helicopter Radar

Lasse Rabenstein, Hansruedi Maurer, Andreas Bauder,
Lisbeth Langhammer, Patrick Lathion, Martin Funk

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GEOSAT SA
Bureau d'ingénieurs et géomètres officiels EPF/SIA

1. Introduction

The environmental conditions for hydropower in Switzerland will change with the ongoing retreat of the alpine glaciers. Strategies to adapt to these changes require a better knowledge about the present volume and geometry of alpine glaciers, as the following two examples show:

I

- **Retreating glaciers mean a loss of large water reservoirs**
- New dam lakes in eventually ice free glacier valleys are a solution (see example Trift glacier valley in Figure 1)
- Potential but still glacerized dam sites can be identified with **helicopter ground penetrating radar**.

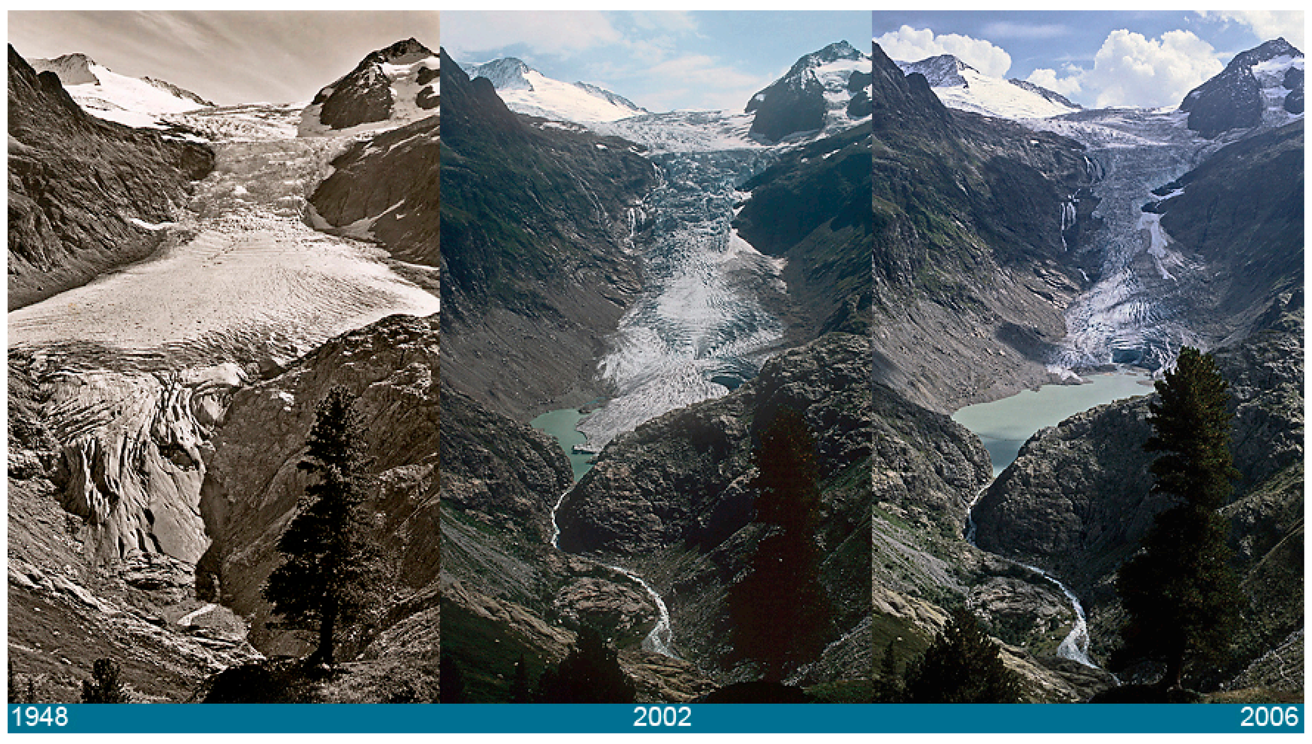


Figure 1: *The retreating Trift glacier. http://www.gletscherarchiv.de*

II

- **Retreating glaciers change the annual river run-off**
- A quantification of the future river run-off is needed for an adequate adaption of hydropower infrastructure
- Unfortunately, **the present glacier ice volume** is a highly sensitive parameter for numerical run-off simulations (see Fig 2)
- Future predictions remain uncertain as long as present ice volume estimations have a high uncertainty (>10%).

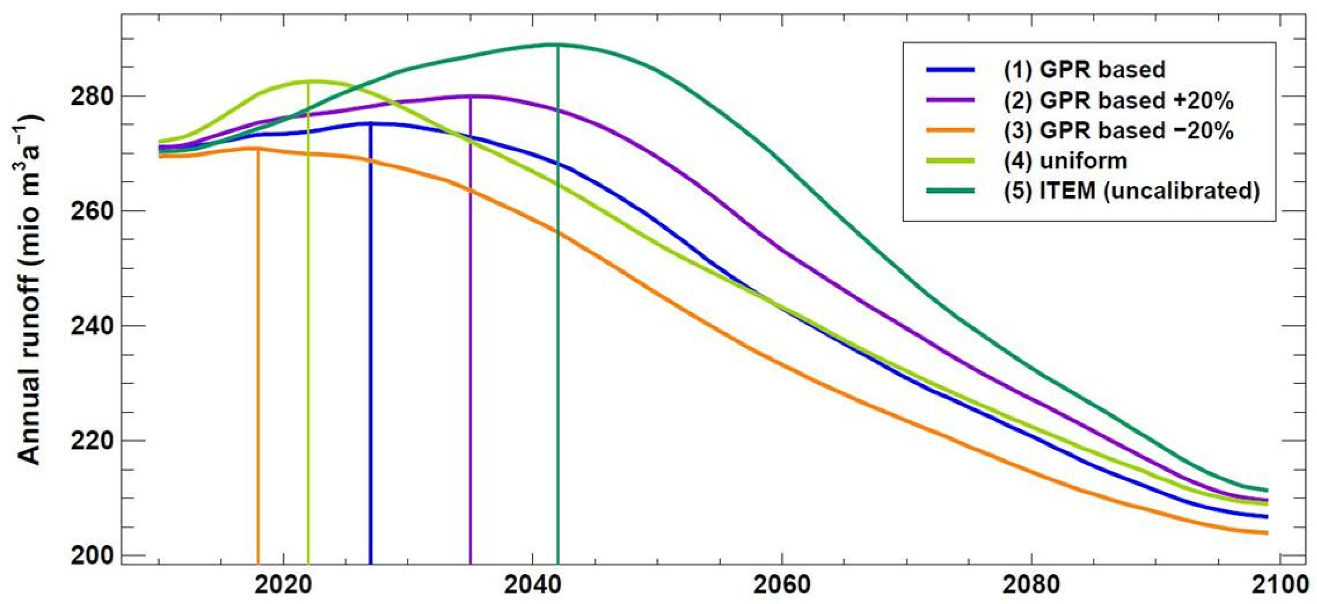


Figure 2: *River runoff predictions for the Mauvoisin region simulated by Gabbi et al, 2010. Different colors refer to different initial ice volumes.*

2. Project Outline and Progress

- An accurate estimation of the Swiss ice volume estimation is the ultimate goal.
- We estimate a duration of three winter seasons of measuring before an ice volume can be given.
- Ongoing local studies within SCCER-SoE will be supplied with thickness data, **check the posters of** :
  - **Farinotti et al.,** Towards decadal runoff predictions for high-alpine catchments
  - **Schaefli et al.,** Importance of glaciers for CH hydropower

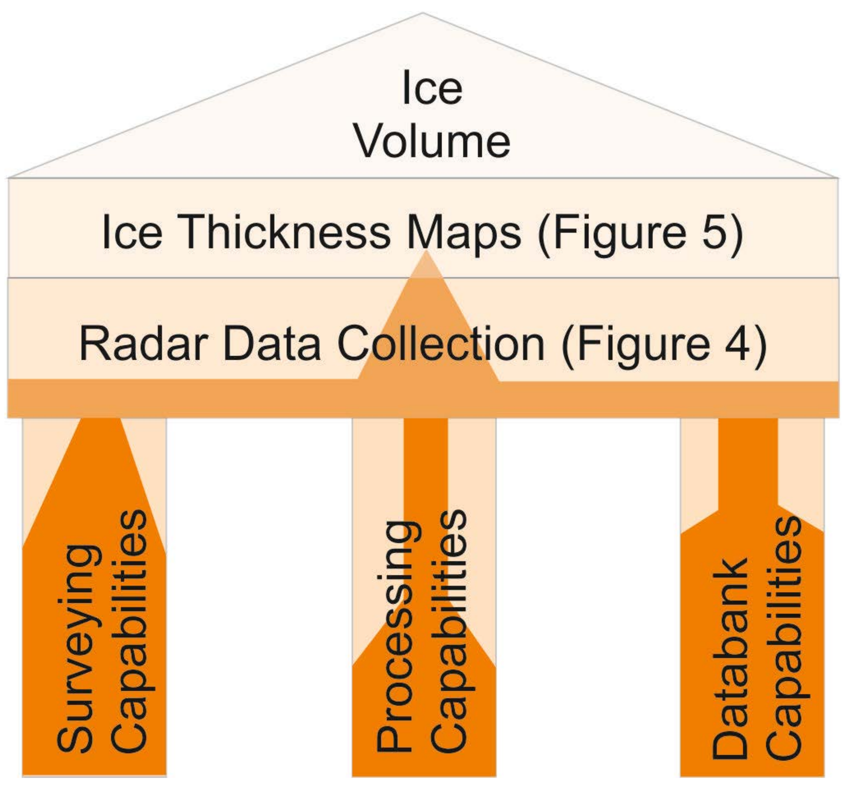


Figure 3: *Project sketch. Three "pillars" of capabilities are needed before the "roof", i.e. the ice thickness data, can be gathered. Dark shaded colours are the completed sections by 09/2015 and light shaded colors the planned sections.*

3. Improving Surveying Capabilities

- In Spring 2014 limited ice penetrating radar capabilities were available, which resulted in bad images (Fig 4a).
- Better images could be obtained by using **lower frequencies** (app 20 MHz) and **antenna orientations** perpendicular to the (mostly unknown) topography gradient in the subsurface.
- The newly constructed helicopter radar system uses **two 25 MHz antennas simultaneously in a cross orientated fashion** and produces higher quality images of the glacier bed (Fig. 4b).

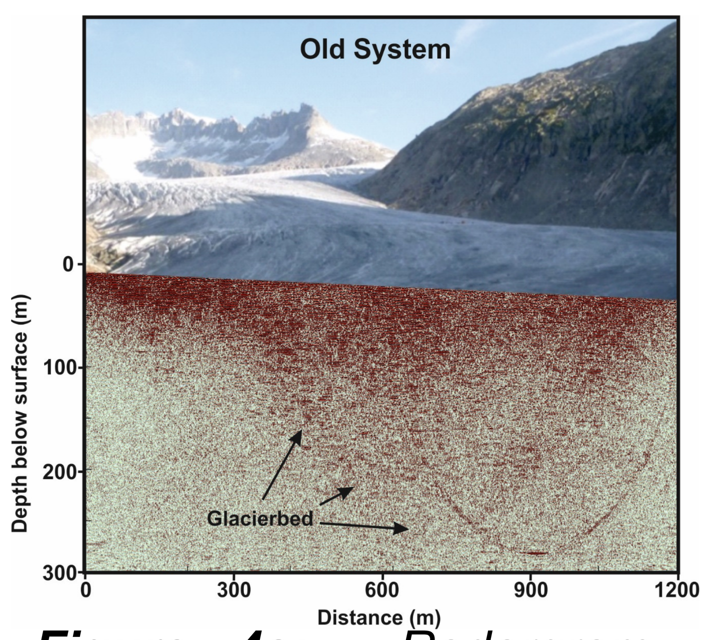


Figure 4a: *Radargram across a glacier tongue using the old 67 MHz system*

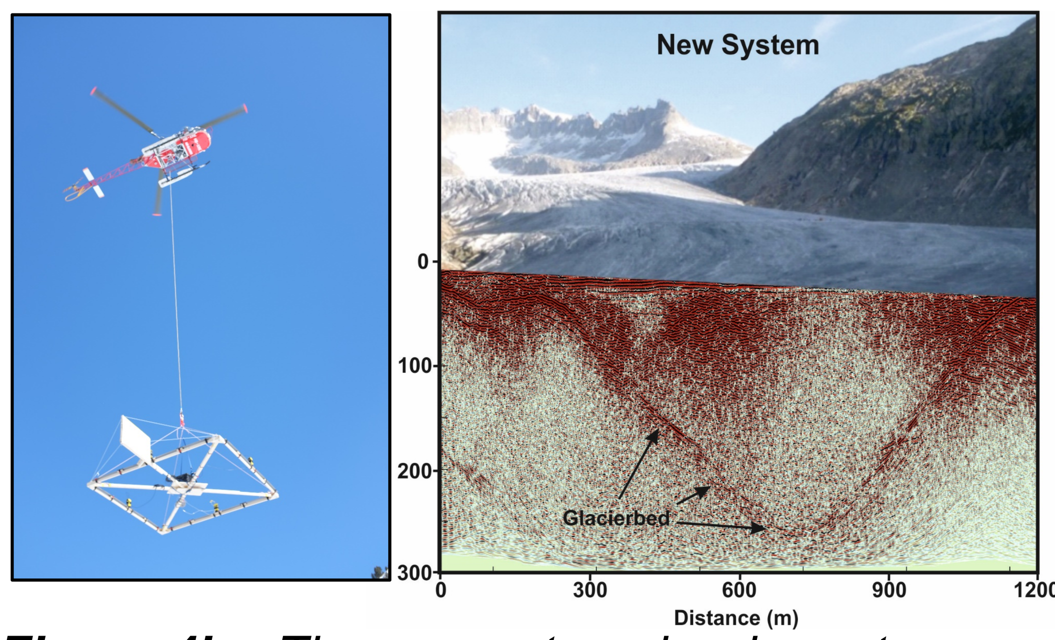


Figure 4b: *The new external radar antenna system and a resulting radargram, flown on the same line as Figure 4a.*

4. Final Product: Ice thickness maps

- Identified glacier bed profiles (see Fig. 4b) are fed as additional constraints into a glaciological ice thickness estimation model (e.g. Farinotti et al., 2009)
- Eventually, thickness maps of all significant glaciers in Switzerland will be calculated (see Fig 5 as an example)

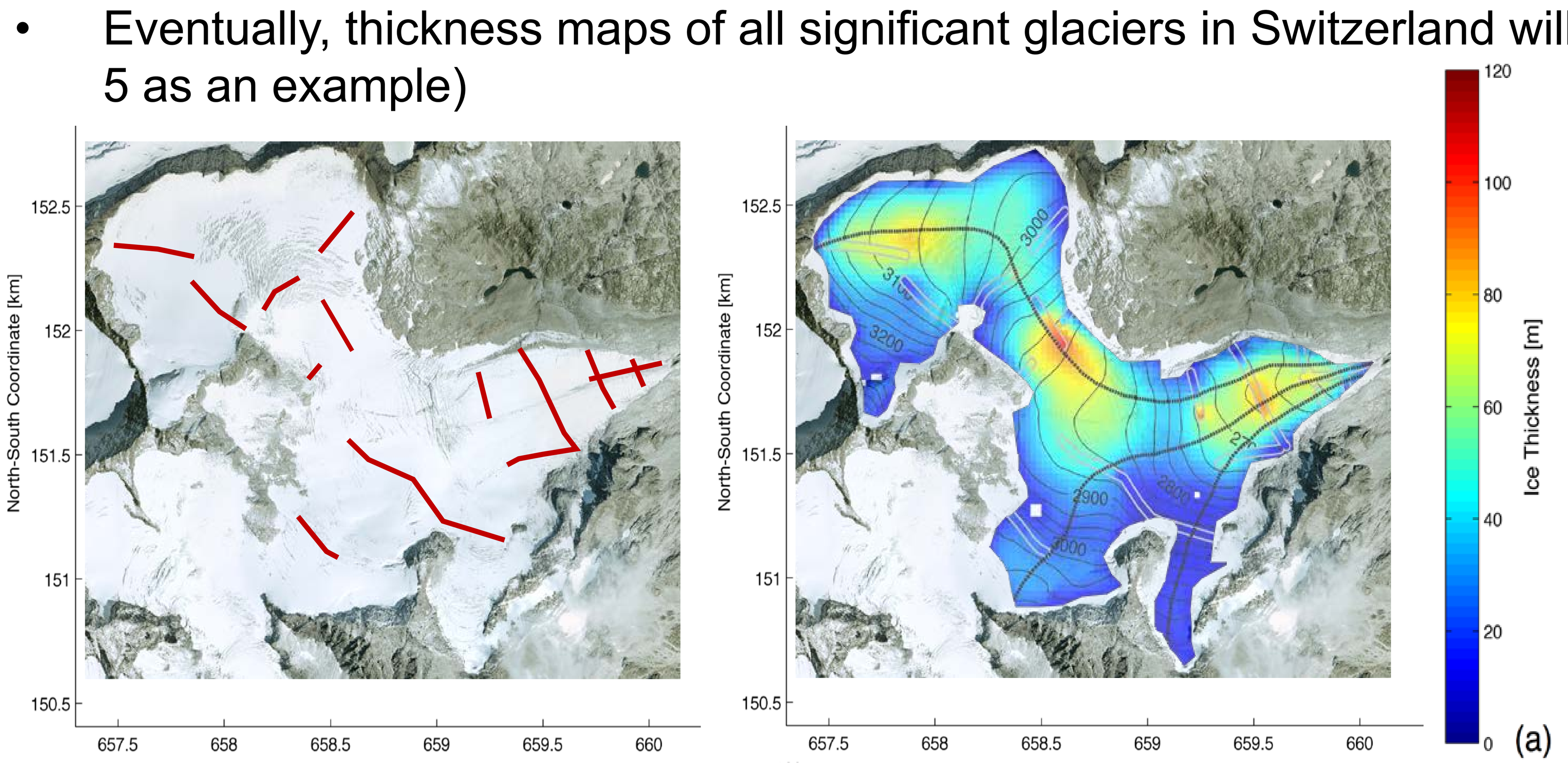
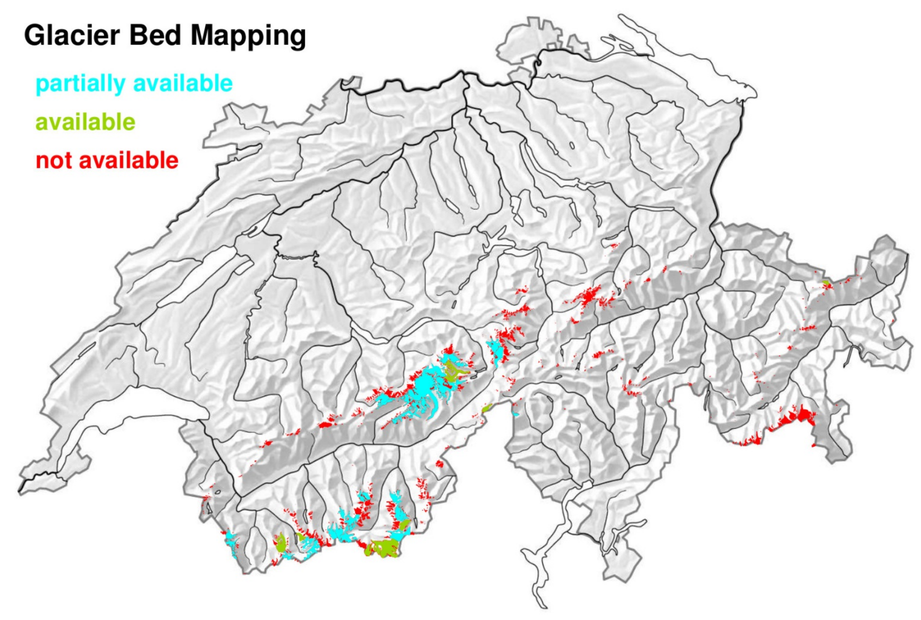


Figure 5: *Radar survey transects flown on the Minstiger glacier and the resulting ice thickness map, based on Lucas (2014).*

5. Outlook

The map below shows all glacerized regions in Switzerland. Blue and red areas are going to be surveyed within the next years. In addition more research will be done in improving our surveying, processing and databank capabilities.



References: Farinotti, D., et al. "A method to estimate the ice volume and ice-thickness distribution of alpine glaciers." Journal of Glaciology 55.191 (2009): 422-430.
Gabbi, J., et al. "Ice volume distribution and implications on runoff projections in a glacierized catchment." Hydrology and Earth System Sciences 16.12 (2012): 4543-4556.
Lucas, C., "Helicopter Borne and Ground Penetrating Radar Measurements on Alpine Glaciers", ETH Zurich Master thesis (2014)

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Generation of very high resolution scenarios to investigate climate change impact on hydropower operation

Nadav Peleg, Simone Fatichi, Paolo Burlando, Sven Kotlarski, Isabelle Bey

Abstract

The main objective of this project is to generate very high-resolution climate scenarios to assess the impact on hydropower production and operation for the mid- and- end of the 21st century using the state of the art global and regional climate models and greenhouse gas scenario ensemble.

This is best done by using stochastic methods for downscaling of climate variable from global / regional scale to local scale, as this allows to explore the uncertainties resulting from natural-stochastic climate variability.

To this end, a new stochastic weather generator is being developed (AWE-GEN-2d) with the aim of formulating a high spatial and temporal resolution tool for predicting key climate variables.

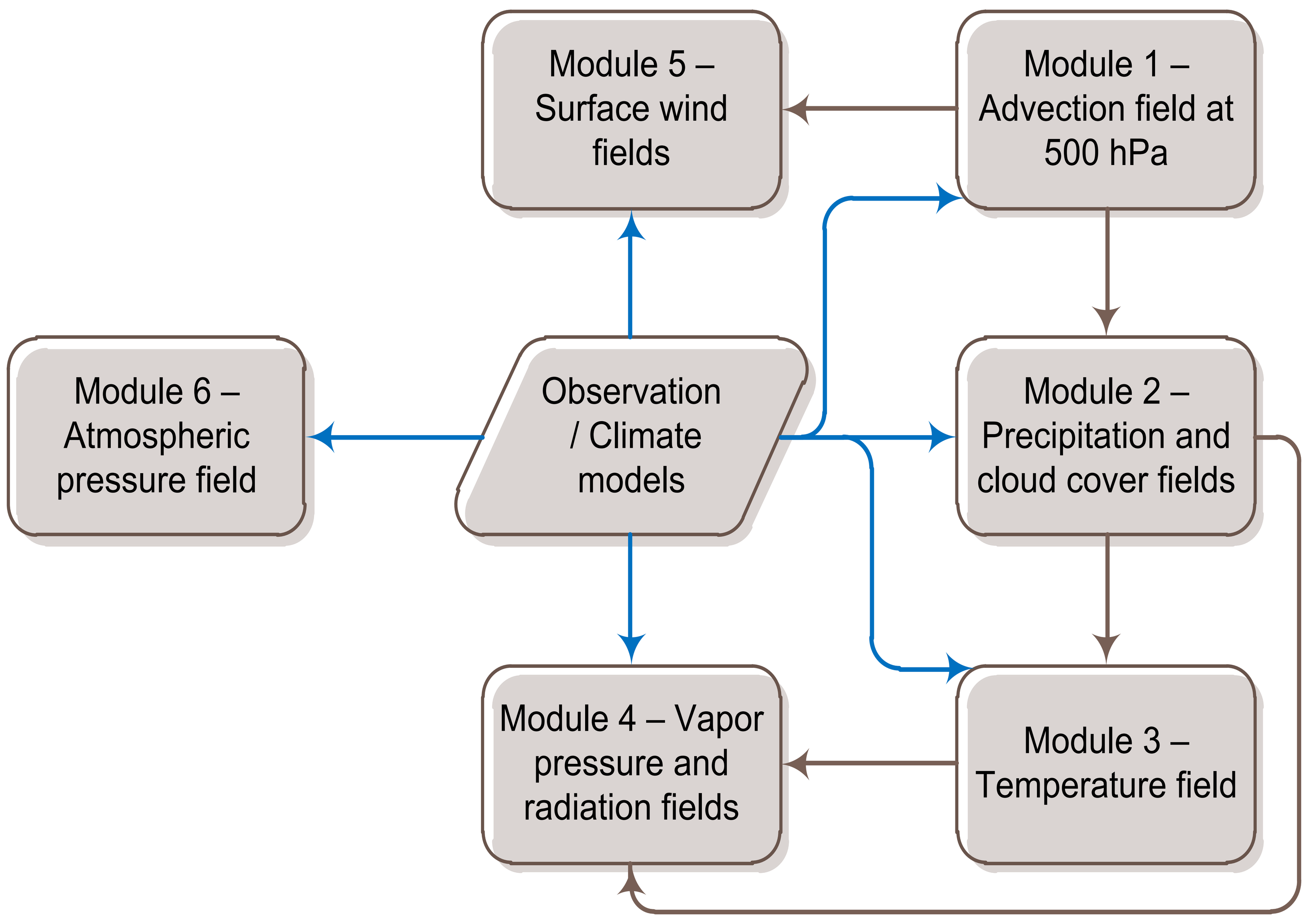
1. Model development

The AWE-GEN-2d (Advanced WEather GENerator for 2-Dimension grid) is being developed following the philosophy of combining physical and stochastic approaches to generate gridded climate variables in a high spatial and temporal resolution (e.g., 2-km and 5-min for precipitation and 100-m and 1-h for temperature).

The AWE-GEN-2d is a substantial evolution of the hourly-point Advanced WEather GENerator (AWE-GEN) presented by Fatichi et al. (2011). Integrated into the AWE-GEN-2d are concepts from the Space-Time Realizations of Areal Precipitation model introduced by Paschalis et al. (2013), the High-Resolution Synoptically conditioned Weather Generator developed by Peleg and Morin (2014), and the Wind-field Interpolation by Non Divergent Schemes presented by Burlando et al. (2007).

The AWE-GEN-2d is relatively parsimonious in terms of computational demand and allows generating many stochastic realizations of current and projected climates in a fast and efficient way.

2. AWE-GEN-2d general scheme

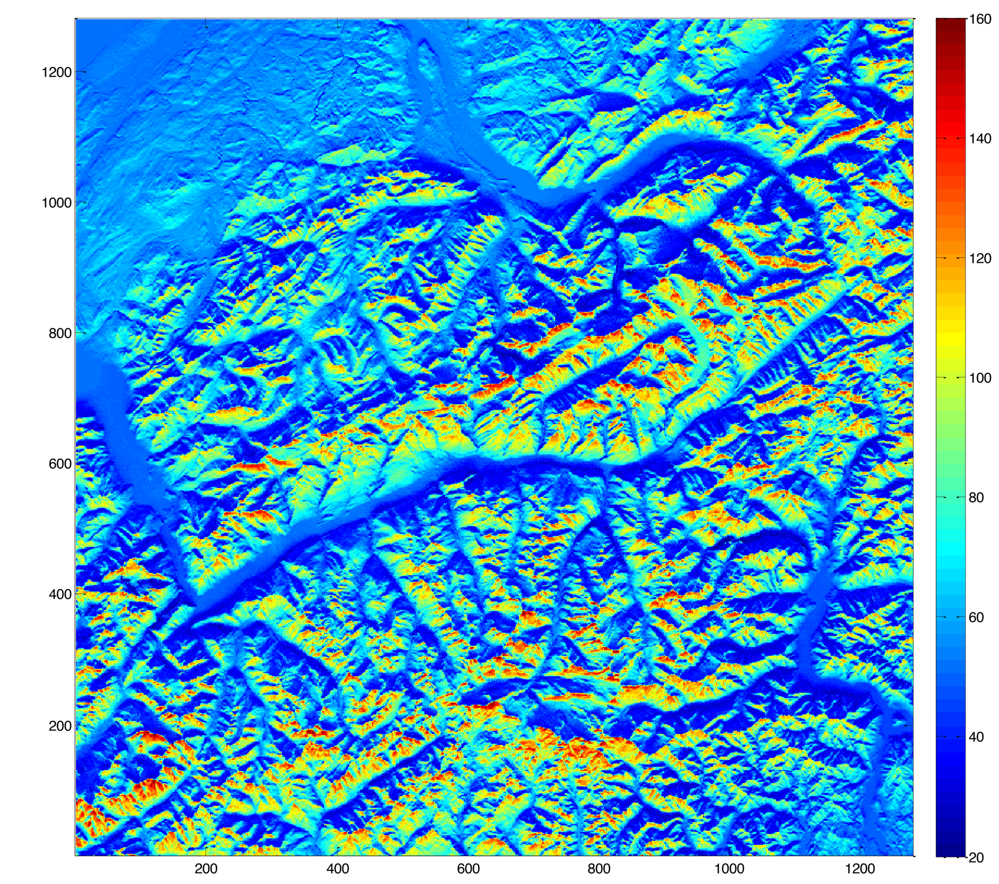


Interdependency exists between different climate variables. Nevertheless, the possibility to run each module separately exists. This allow the end-user to simulate only the required variables for a specific study, saving computation time and disk space.

[1] see poster "Impacts of climate change on hydrology and operation of Mattmark reservoir under business-as-usual production targets" (Task 2.5) by Anghileri et al.

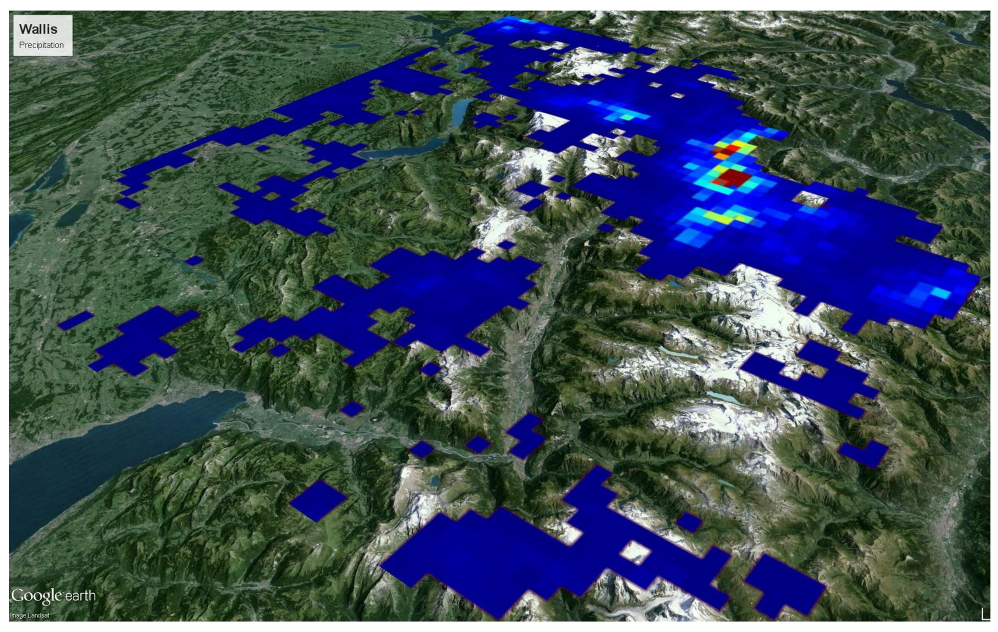
3. Example for the model's high-resolution output

The α-version of the model is being evaluated on the Wallis region. So far we have completed the evaluation of 5 out of the 6 modules composing the model.



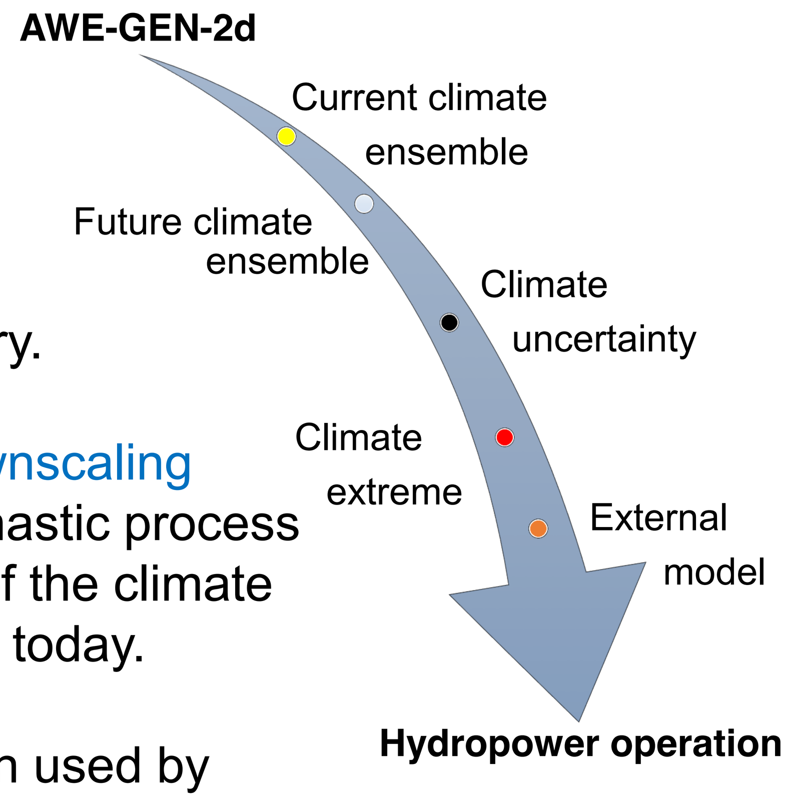
To demonstrate the model high-resolution output performance two figures from the evaluation process were selected.

In the upper figure, the mean incoming global radiation for January is plotted over a 100-m grid.



In the lower figure, a snapshot of the rain field, representing a 5-min in time, over a 2-km grid is presented.

4. Investigation of climate change impact on hydropower operation



The AWE-GEN-2d is at the top of the model chain.

Current and future climate ensembles would be generated for the 21st century.

This will be done by stochastically downscaling the regional climate models. The stochastic process would enable a better understanding of the climate uncertainty and extreme than we have today.

The AWE-GEN-2d products would than used by an external models (e.g., hydrological or geomorphological) operated by other groups to investigate climate change impact on the hydropower operation (e.g., sediment transport, glacier melting, etc.).

An ongoing example of this scheme, investigating the climate change impact on the *Mattmark reservoir* (with Task 2.5), refer to [1].

5. Goals and timetable

Phase I

- Releasing a β-version of the AWE-GEN-2d
- Generating climate ensembles based on the latest IPCC's emission scenarios using Euro-CORDEX and CMIP5 models
- Supplying high-resolution scenarios for tasks` partners

Phase II

- Further developing of the model to reduce model's uncertainty
- Integrating data from the state-of-the-science C2SM 2-km climate model to improve model projections
- Analyzing the future climate scenarios for extreme events and uncertainty
- Analyzing reservoir operation sensitivity to current and future climates

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Water Balance of Alpine ski resorts

Grünewald T., Rhyner H., Wolfsperger F., Lehning M.

1. Introduction

Significance of the research

- Rising demand of water under a changing climate
- Conflicting use of water for tourism, energy production, drinking water supply and agriculture
- Little quantitative research on water balance in Alpine resorts that could be used for prediction

Figure 1: Snow making

Skiing industry & technical snow

- High economic importance of winter tourism especially at regional scale (e.g. tourism accounts for 30% of gross domestic product in Grisons)
- Ski runs cover about 22500 ha of Switzerland;41% with technical snow (Fig.2)
- Technical snow (Fig. 1, 4) is a key requirement for modern ski tourism
- Tendency rising due to climate change adaption and customer demand (Fig. 2)

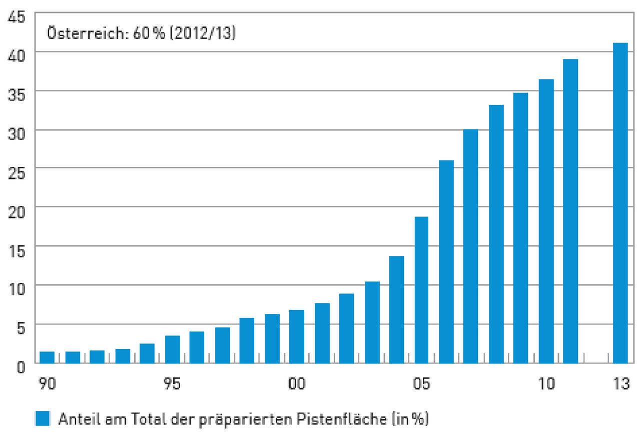

Figure 2: Portion of ski runs with technical snow Source: Seilbahnen Schweiz

Water demand of ski resorts

- 18 to 37 mio m^3 of water per year are used for technical snow production (up to 4000 m^3 /ha)
- Water is taken from streams and reservoirs, temporally stored in the snow pack and released during snow melt
- Most snow is produced from November till January when natural water supply is lowest (Fig. 3)
- Significant portions of water is lost due to evaporation, sublimation and wind drift
- Significance at the local to regional scale: e.g. 1/3 of drinking water of city of Davos is used for snow making

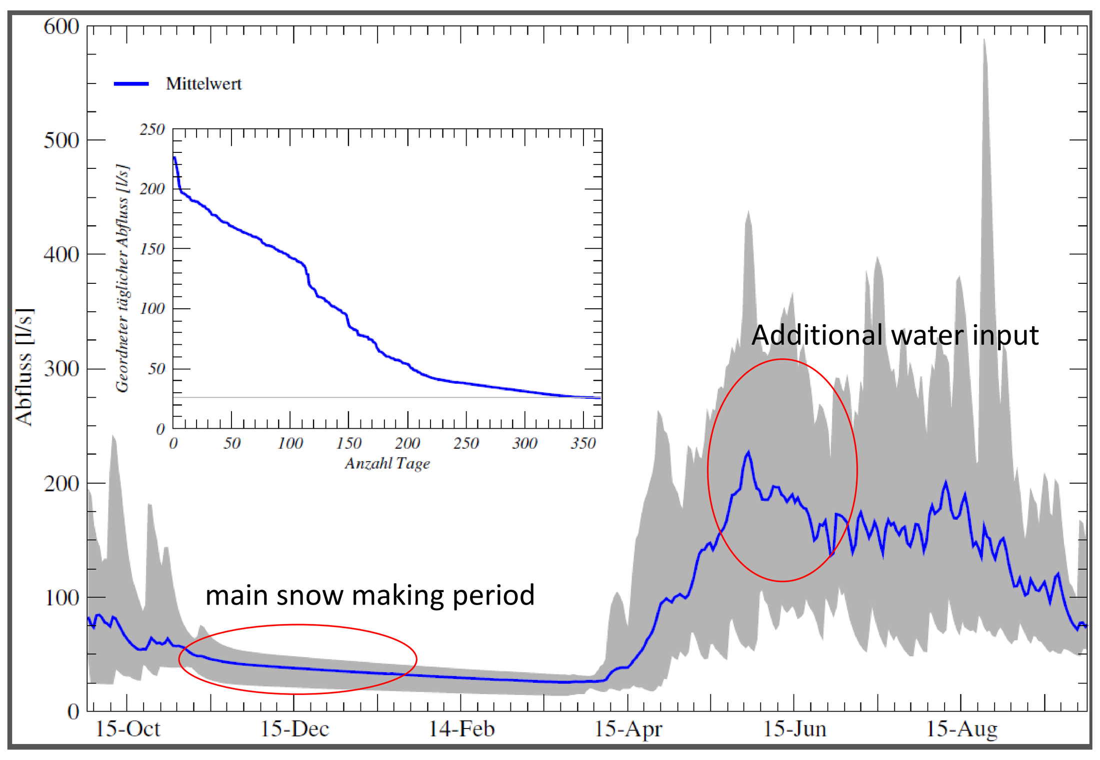

Figure 3: Simulated discharge of a 1,7 km^2 catchment in the Parsenn ski resort (Davos) for 10 years of data. The inlay shows ranked daily discharge with the grey line showing the residual flow Q347.

2. Background: Technical snow

Water droplets are emitted by snow machine and freeze due to heat and mass transfer to the atmosphere (Fig. 4)

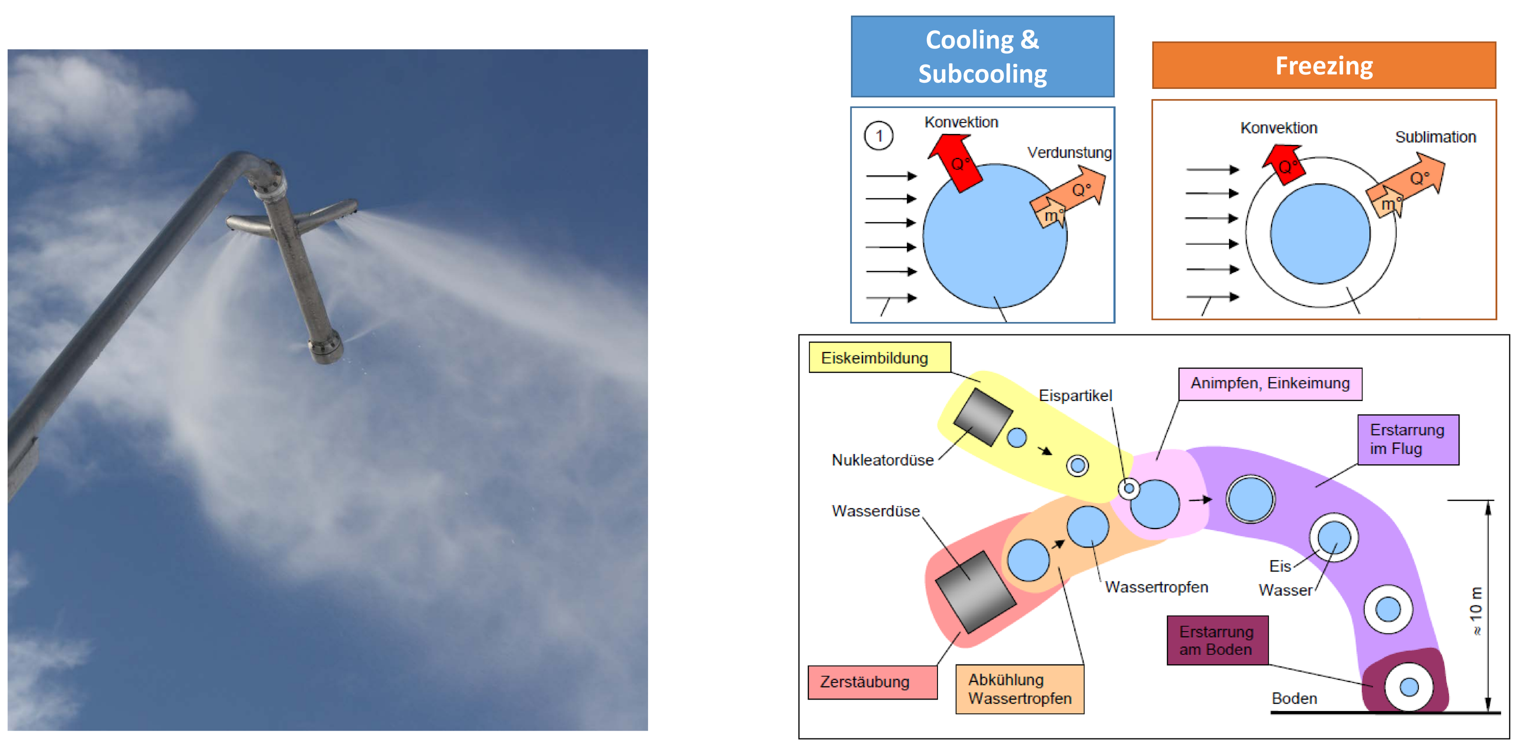

Figure 4: Physical processes during technical snow production

3. Objectives

- Improve the understanding of the winter water cycle in Alpine valleys with winter sports infrastructure
- Quantify water losses due to the production of technical snow
- Analyse demands and consequences of snow management under a changing climate
- Develop a model chain to simulate snow dynamics in ski resorts
- Develop tools for advanced resource management (water and energy) for practical application in ski resorts

4. Methods

Development of a **model chain** (Fig. 5) to simulate snow dynamics in ski resorts, including technical snow

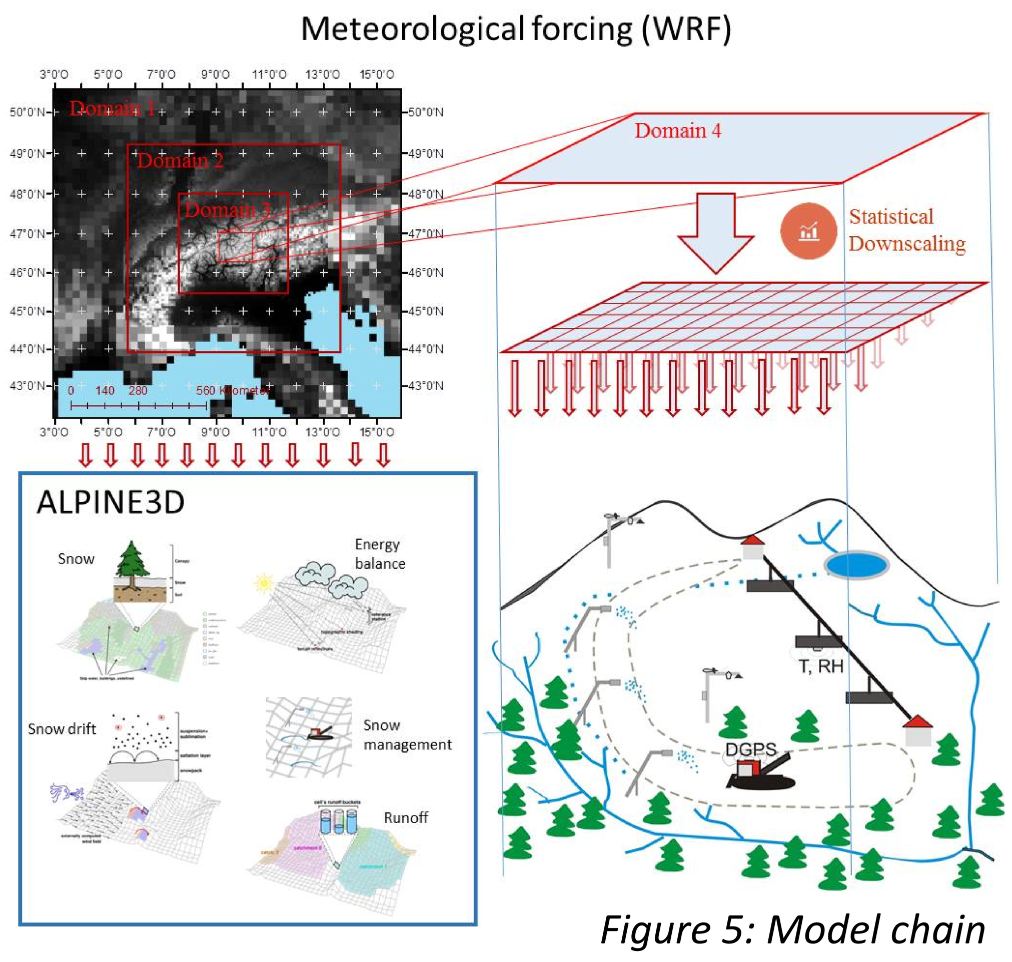

Figure 5: Model chain

- Simulation of snow making process
- Mass balance of snow making at scale of single snow machine (modelling & measurements)
- Modelling of snow dynamics with respect of snow management

Field observations

- Quantification of water losses during technical snow making at scale of single snow machine by terrestrial laser scanning (Fig. 6)
- Assessment of specific snow characteristics of ski runs for model parametrization and verification

Figure 6: Terrestrial laser scanning (left) and manual snow observations (right) during snow making test

5. Status of the project

Preliminary results:

- First field tests indicate **water losses of 10 to 35%** due to sublimation and wind drift (Fig. 7); dependent on settings
- Model chain is under development

Funding:

- Research proposal submitted to Swiss National Science Foundation
- CTI project in preparation

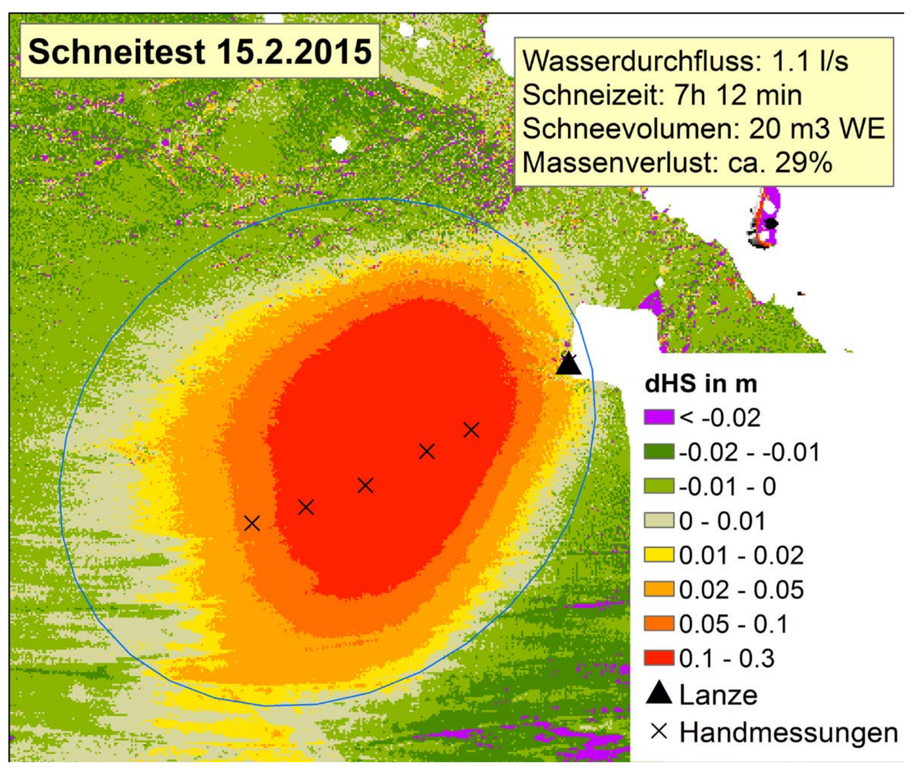

Figure 7: Result of snow making test

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Potential for future hydropower plants: A systematic analysis in the periglacial environment

I. Delaney, D. Ehrbar, L. Schmocker, A. Bauder, M. Funk, D. F. Vetsch, R. M. Boes – VAW, ETH Zurich

1. Introduction

Climate change and glacier retreat have different impacts on hydropower plants in the periglacial environment:
+ increase of reservoirs inflow in the next decades due to glacier melt and decreased storage of precipitation as snow or ice.
– increase of sediment input in reservoir due to the exposure of easily erodible areas and sub-glacial sediment transport

Increased water discharges favor hydropower operations, but larger sediment discharges pose challenges in terms of construction, operation and maintenance.

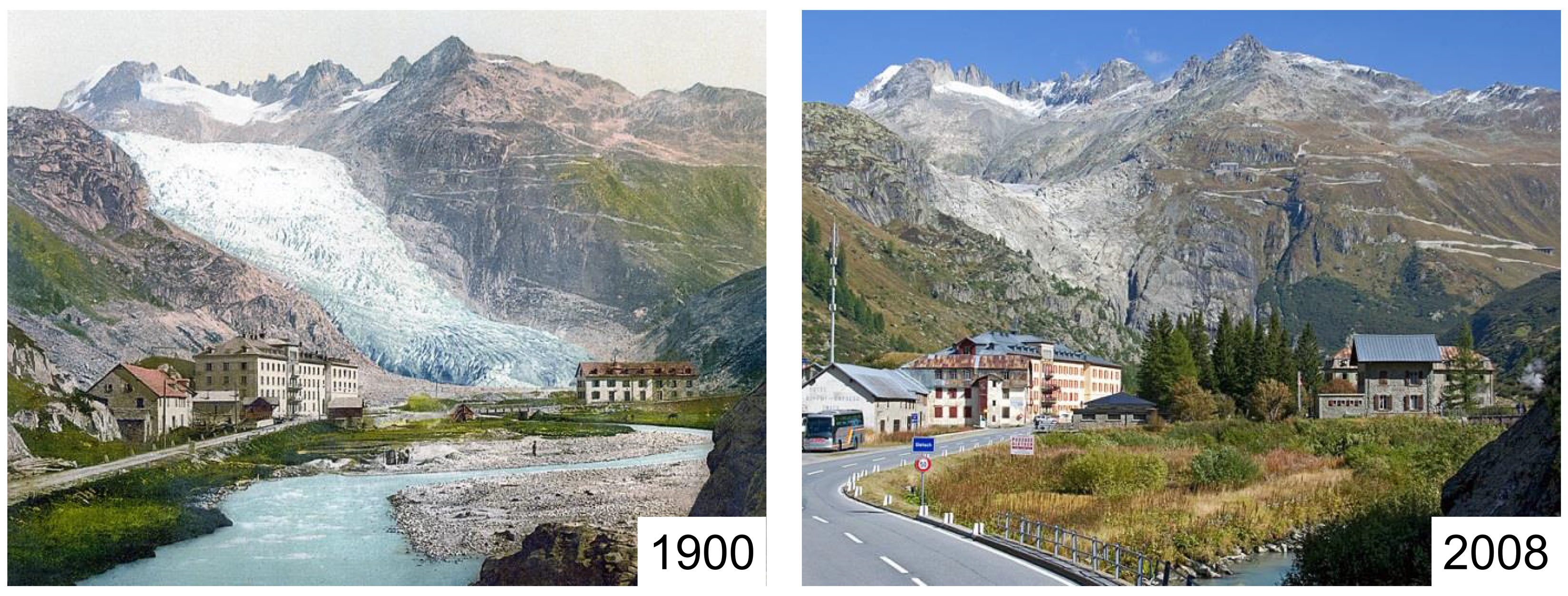

Figure 1: Retreat of Rhonegletscher.

2. Objectives and concepts

The project aims to quantify future water and sediment discharges at selected hydropower sites and to model reservoir sedimentation. To understand the governing processes and parameters, a measuring campaign is carried out in 2015 and 2016.

The main objectives are:
(i) Examine water and sediment discharges for selected glaciated catchments and forecast the future evolution of these catchments
(ii) Model the future reservoir sedimentation using numerical models, coupled with climate models and estimate the reservoir life-span

This allows to evaluate current and future hydropower plants regarding their economic feasibility and to plan sediment evacuation measures.

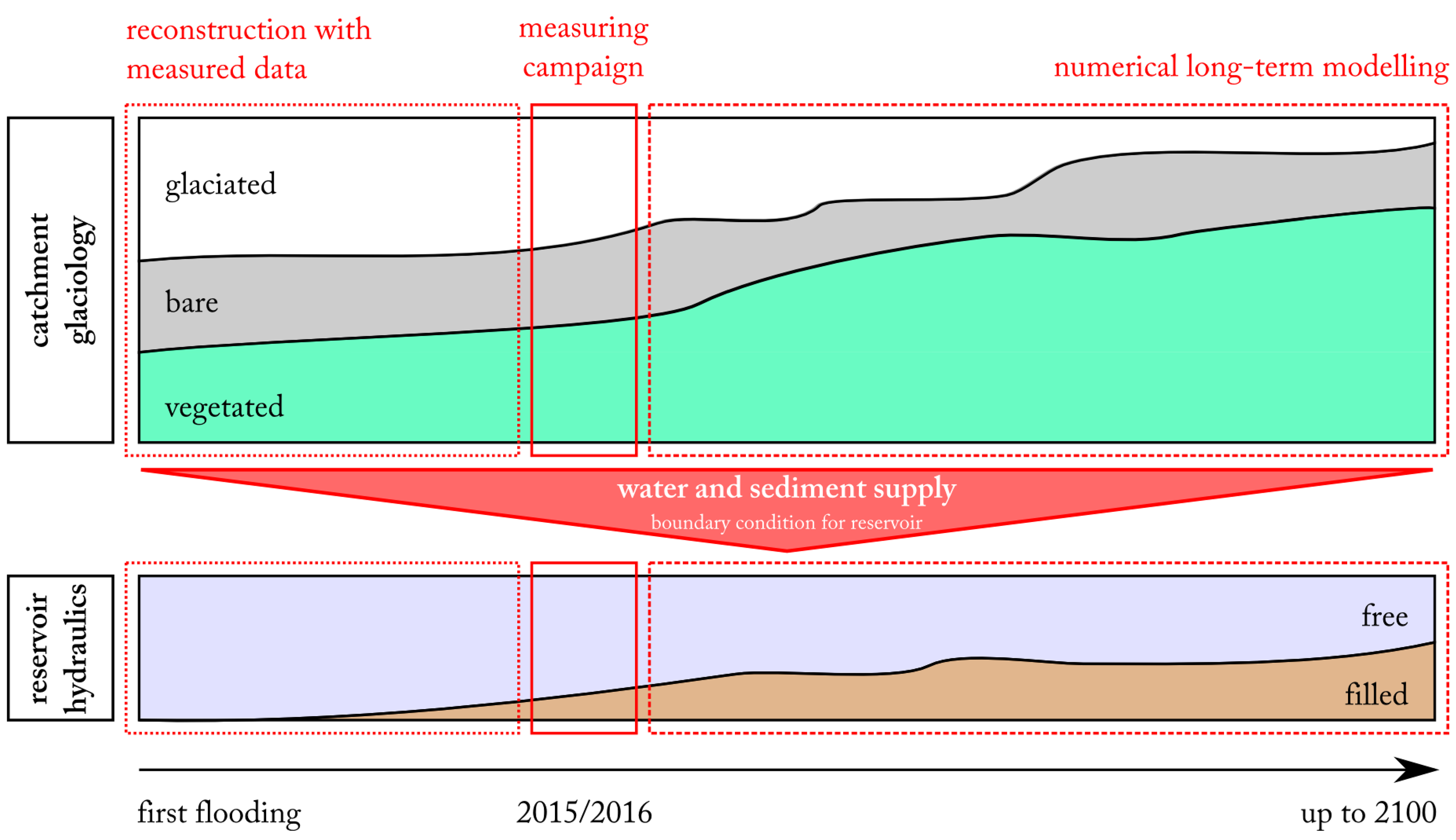

Figure 2: Sketch of the project framework

Acknowledgements
This project is financially supported by the Swiss National Science Foundation (SNF) within the National Research Programme NRP 70 "Energy Turnaround" Project No . 153927 and technically supprted by Electra-Massa (Alpiq), Forces Motrices de Mauvoisin (Axpo), Ofima/Kraftwerk Aegina, HYDRO-Exploitation and Grande Dixence.

3. Subproject "sediment production"

To assess the propensity for glaciers to supply sediment to hydropower reservoirs, two processes must be investigated:
1) Erosion of unconsolidated sediment in the glacier fore-field.
2) Climate's effect on availability and transport of sub-glacial sediment.

Table 1: Characteristics of investigated glaciers

Catchment	Approx. Area [1973, km^2]	Length Change [1975, m]	Fore-field (year formed)
Griesgletscher	6.23	-697.8	yes (1986)
Aletschgletscher	86.63	-1325.4	no
Gornergletscher	59.73	-1085.7	yes (2007)

Photogrammetry: Aerial photos will be used to asses erosion quantities in the glacier fore-field.

Instrumentation: The sediment transport from the glacier is determined using Turbidity meters and water samples.

Modeling: Glacier drainage and melt models forecast future sedimentation from glaciers.

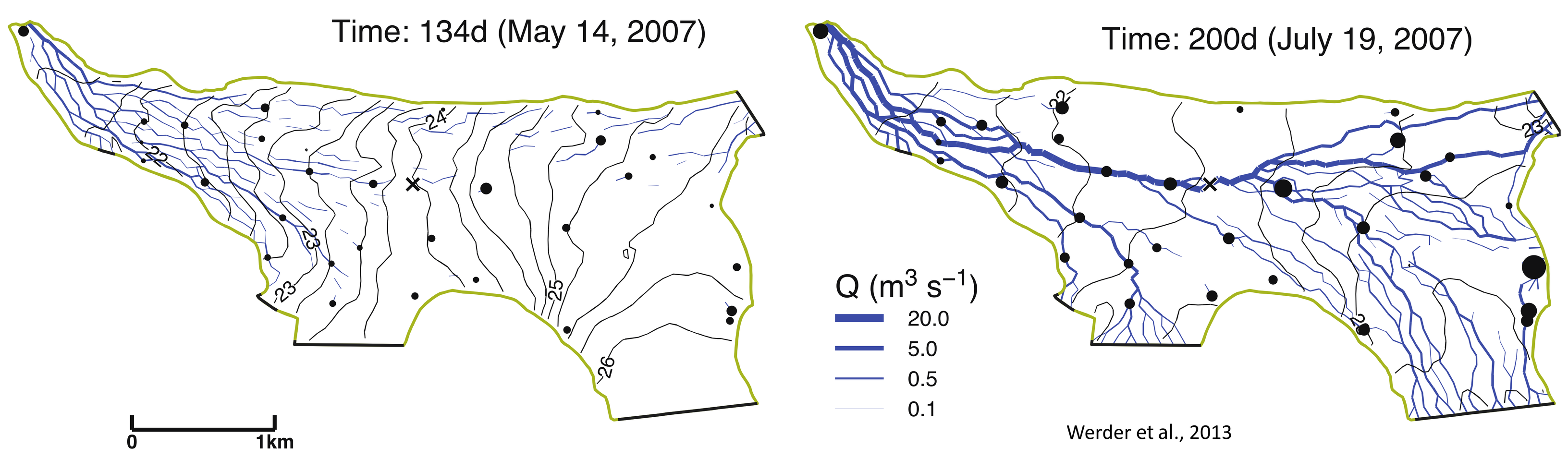

Figure 3: Glacier drainage system model on the Gornergletscher driven with seasonal melt. From Werder et al., 2013.

4. Subproject "deposition of sediment"

Three reservoirs where chosen for prototype measurements (Table 2). V is the volume of the reservoir, z is the full supply level, A the watershed area and P the current glaciation of the catchment.

Table 2: Characteristics of investigated reservoirs

Reservoir	***V*** [hm^3]	***z*** [m a.s.l.]	***A*** [km^2]	***P*** [%]
Griessee	18	2385	10	61
Lac de Mauvoisin	180	1961	114	46
Gebidem	9	1436	198	64

A combination of six measuring methods is applied: (i) Secchi disk, (ii) Niskin bottle sampler, (iii) Van Veen Grab sampler, (iv) Acoustic Doppler Current Meter ADCP, (v) Laser In-Situ Scattering Transmissometry LISST and (vi) Remote Sensing. The aim is to determine (i) the particle size distribution of deposited sediments and sediments in suspension, (ii) the concentration profiles of suspended solids and (iii) the velocities distribution in the reservoir.

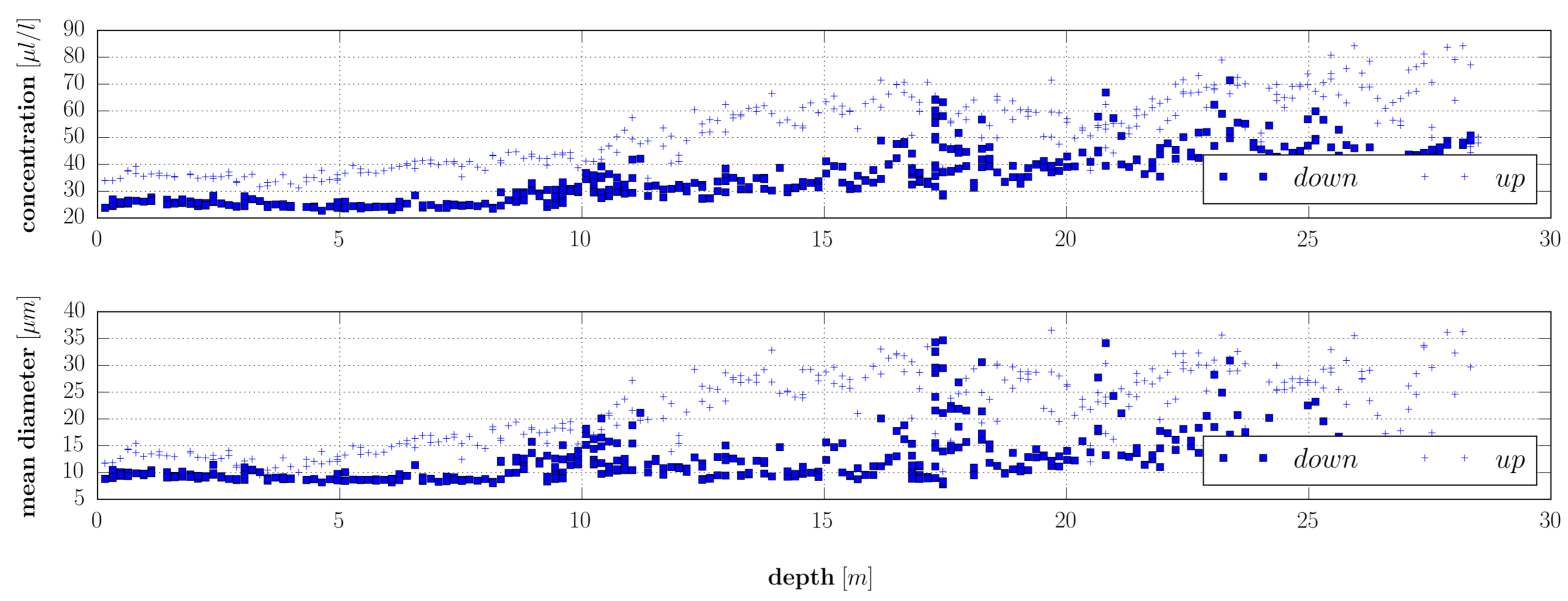

Figure 4: LISST-profile taken at Griessee (18 August 2015)

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Climate change projections for hydropower – a review

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1. Overview: model-based climate change assessment

- State-of-the art climate change impact assessment uses a complex **simulation framework** including
  - ➢ A system model chain (Figure 2)
  - ➢ 3 simulation phases & 4 result analysis steps (Figure 3)
- Impacts on hydropower production (HPP) depend HPP type
  - Run-of-the river: impact can be deduced from runoff statistics (Figure 1)
  - (Pump-)storage hydropower: impacts = f(management)

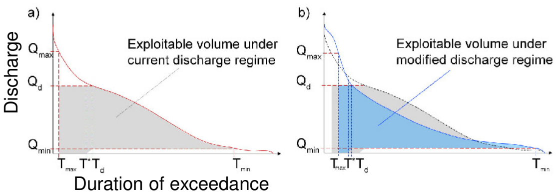

Fig. 3: Use of flow-duration curves to estimate the water volume for run-of-river HPP under a) observed and b) an assumed future discharge regime (source: Schaefli, 2015)

- Most existing climate change & HPP studies omit part of the modelling chain:
  - ➢ Most studies *use highly simplified management models*
  - ➢ Studies including ecosystem evolution: extremely rare
  - ➢ Very few studies include sediment simulations

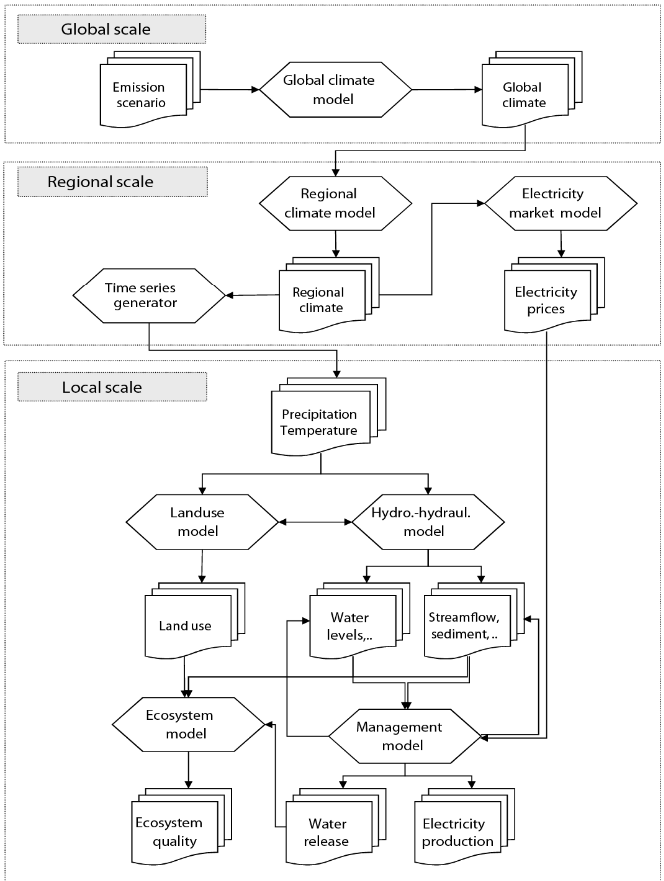

Fig. 1: Model chain for climate change impact simulation. Many more feedback loops between the models could exist. A complete hydropower production (HPP) management model includes HPP operation as well as maintenance work.

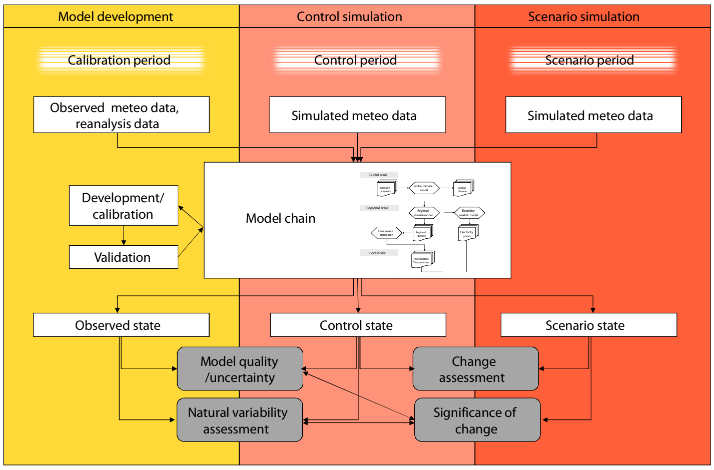

Fig. 3: Simulation framework for climate change impact assessment : colored boxes are the 3 simulation phases, grey boxes the 4 steps of output analysis (Schaefli, 2015)

2. Climate change and Swiss hydropower

- Robust result from recent Swiss research:
  - ➢ Snow-/icemelt influenced catchments will undergo significant regime shifts (Fig. 4) due to warming; future precipitation highly uncertain
  - ➢ Timing of occurrence of regime shifts highly uncertain due to ice volume uncertainty (e.g. Huss et al., 2011)

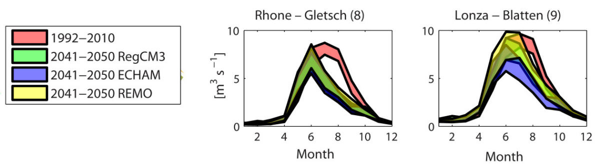

Fig. 4: extracted from Fig. 9 of Fatichi et al., 2015. Original caption: A comparison among simulated annual cycles of streamflow ($m^3 s^{-1}$) for 12 selected river sections. Comparison is between control scenario 1992–2010 and future scenarios 2041–2050 for the stochastic downscaling driven by RegCM3, ECHAM5, and REMO. The colored bands include simulations within the 10th and 90th percentiles of the stochastic ensembles.

- Effects of high Alpine regime shift dampen out for lowland HPP
  - ➢ *Reduction of late summer flows* might propagate far downstream
- Hydrologic extremes & hydropower production: a single comprehensive study: Fatichi et al., 2015 (Upper Rhone River)
  - ➢ Simulation of hydrologic extremes still highly uncertain
  - ➢ High flows might increase
  - ➢ No reliable projections possible regarding future minimum flow conditions

3. Conclusions – challenges for SCCER-SoE

- Highly uncertain climate change projections require combination of impact assessment (A) AND vulnerability assessment (B) (Fig. 5)

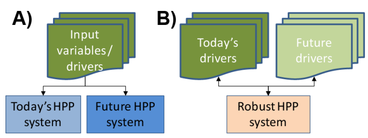

Fig. 5: Illustration of impact assessment (A) and vulnerability assessment (B) for HPP

- ➢ Enhanced hydrologic forecasting for HPP to handle uncertain future climates AND uncertain future demand patterns

References

Fatichi et al., 2015, *High-resolution distributed analysis of climate and anthropogenic changes on the hydrology of an Alpine catchment.* Journal of Hydrology

Huss et al., 2011: *High uncertainty in 21st century runoff projections from glacierized basins*, J. of Hydrology

Schaefli, 2015, *Projecting hydropower production under future climates: a guide for (…)*, WIREs Water

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Development of a methodology for extreme flood estimation

Fränz Zeimetz(1), J. Garcìa Hernàndez(2), F. Jordan(3), G. Artigue(3), J.-A. Hertig†, J.-M. Fallot(4), R. Receanu(4), A. J. Schleiss(1)

(1) Laboratoire de Constructions Hydrauliques, Ecole Polytechnique Fédérale de Lausanne, 2) Crealp; (3) e-dric.ch Sàrl; (4) Hertig et Lador SA

1. Introduction

The development of a methodology for **extreme flood** estimation is the aim of the project CRUEX++. This project follows the CRUEX project which aimed at the development of a PMP-PMF methodology (PMP=Probable Maximum precipitation, PMF=Probable Maximum Flood). Numerous tools, models and methods have been developed during the last years. The goal of the CRUEX++ project is to combine and enrich these elements leading to a methodology for extreme flood estimations in order to verify dam safety. A PhD thesis has been initiated in 2012 to lead this project and to conclude on a final methodology.

2. Approaches

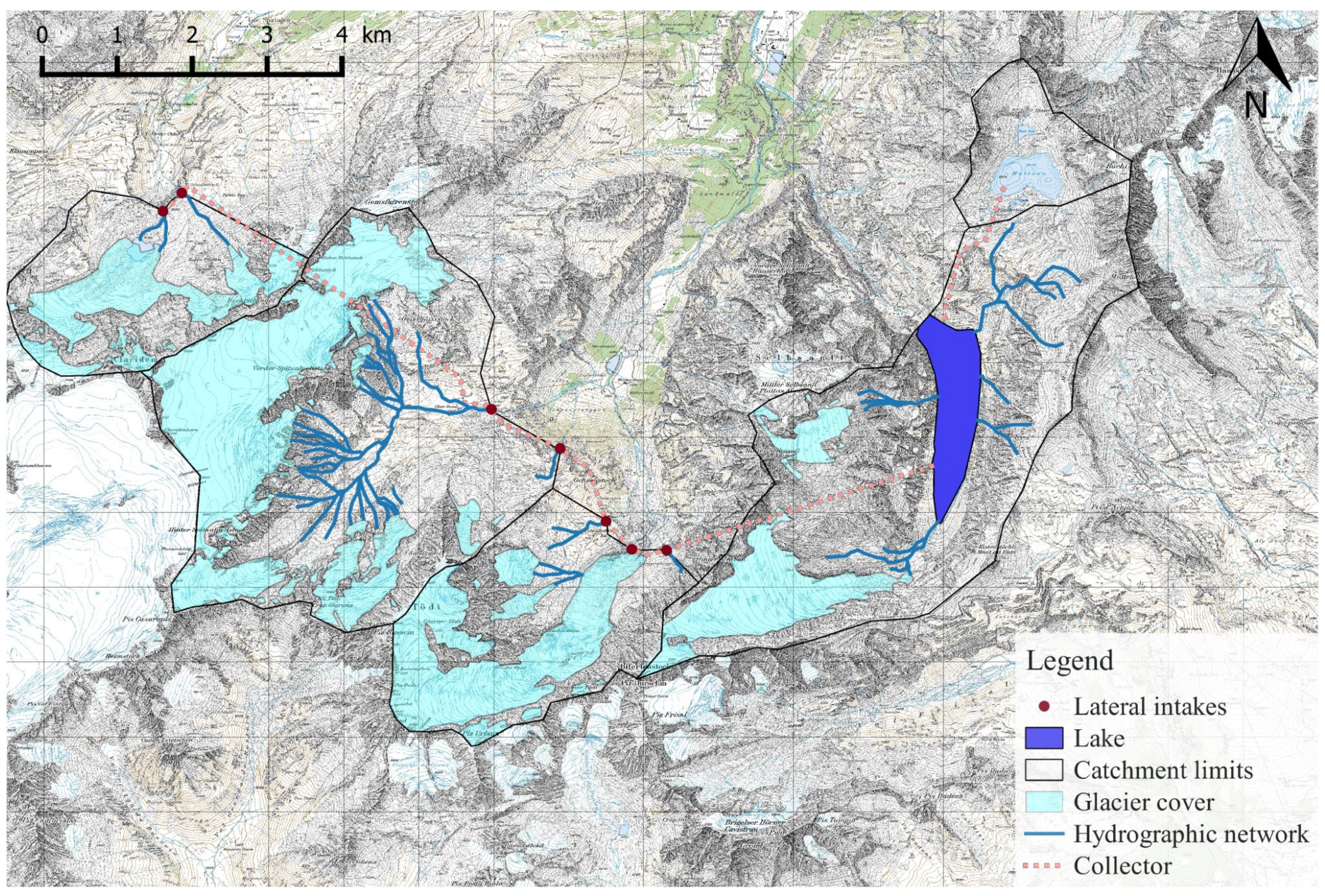
The 2 main families of approaches taken into account are the statistically based methods and the simulation based methods.

In the context of the **statistically based methods**, the theory of extremes, englobing the General Extreme Value Distribution (GEV) and the Peak Over Threshold Method (POT), as well as the GRADEX method are included.

In the domain of the **simulation based methods**, the semi-distributed conceptual hydrological model GSM-Socont is used in a modified version. This model allows Precipitation-Discharge simulations, respecting the contributions of snow fall, surface runoff, infiltration as well as snow and glacier melt.

The **PMP-PMF approach** based on PMP maps, elaborated during the CRUEX project is also considered as part of the simulation based methods

3. Case study of Limmernboden

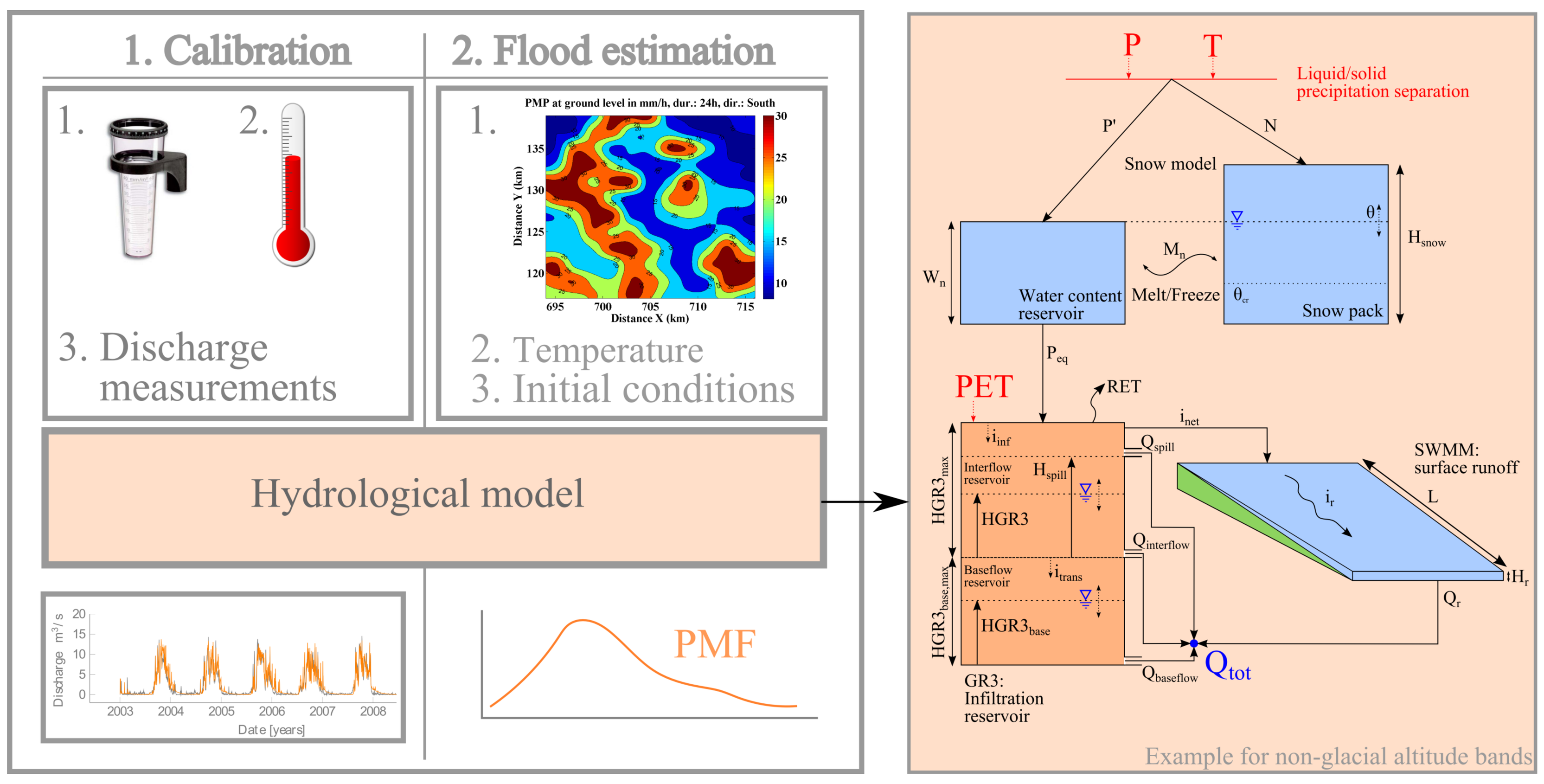


- Northern Swiss Alps
- Area: 17.8 km^2
- 7 lateral intakes
- Additional catchment: 31.8 km^2
- Total glacier cover: 17.5 km^2
- Altitude range: 1858-3614 masl
- Karstic behaviour

- A detailed description of the case study has been presented at IUGG 2015 and can be consulted by scanning the following QR code

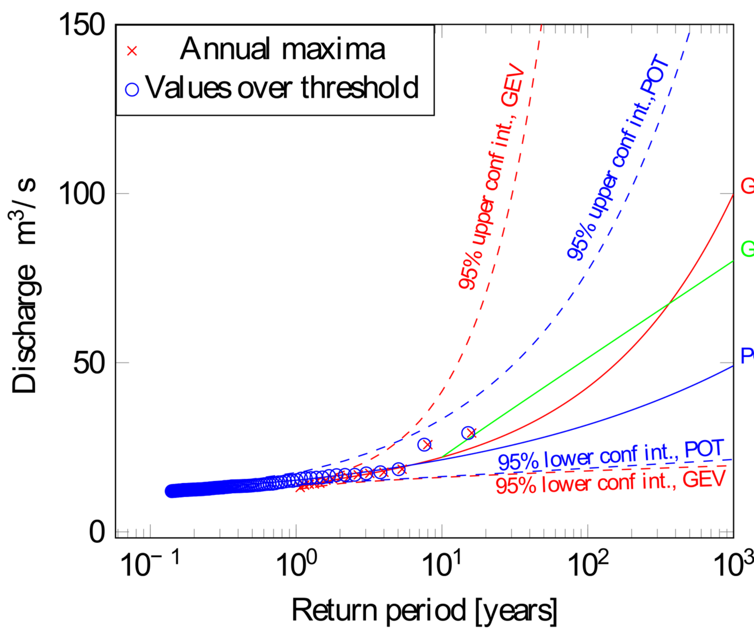
- 2 approaches are applied
    1. Statistically based methods
    2. Simulation based PMP-PMF method
- The results are compared and discussed

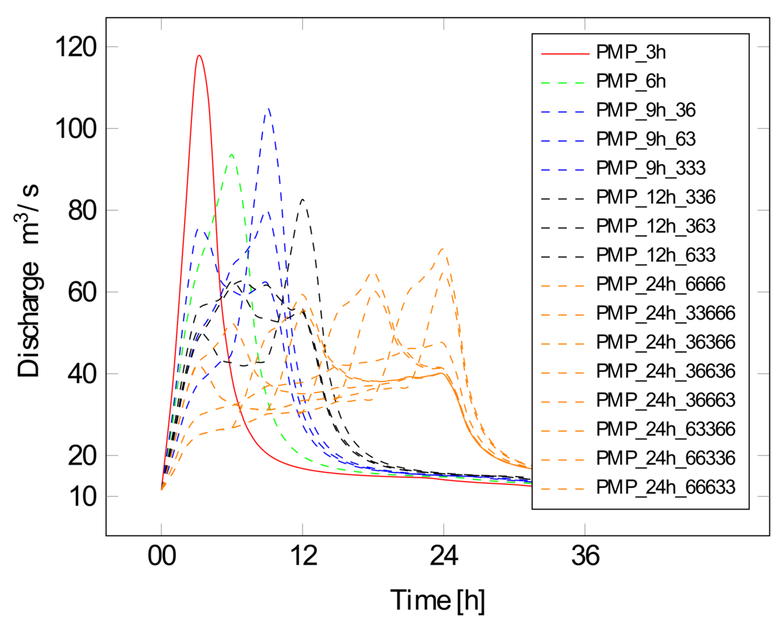
4. PMP-PMF simulation approach



5. Results and discussion

- Statistical extrapolations using GEV, POT and Gradex
- PMP-PMF simulations for different precipitation durations





- Daily to hourly: $Q_{hourly}=1{,}7 \cdot Q_{daily}$

  The factor of 1,7 has been determined by hourly and daily simulations over the whole period from 1997 to 2009.
- Critical PMF from 3h-PMP
- Comparison between the PMF and the statistical estimation by ratio R defined below:

$$R = \frac{Q_{PMF}}{Q_{stat}}$$

- Safety flood: $Q_{safety}=1.5 \cdot Q_{hourly}$

R	Q_{GEV}=255 m³/s	Q_{POT}=126 m³/s	Q_{Gradex}=204 m³/s
$Q_{PMF,3h}$=116 m³/s	0.45	0.92	0.57

The results show that the statistical estimates are higher than the PMF. Different reasons can be stated:

- PMP data (maps) with limited choice of precipitation duration.
- Not enough data for reliable GEV or Gradex extrapolation.
- Gradex ignores the karstic effect.
- POT returns the closest estimation compared to PMF.

6. Conclusions

- The PMP-PMF method may not always overestimate extreme flood.
- Statistical methods can lead to very high estimates (>2 $\cdot$ Q_{PMF}).
- Statistical methods are not recommended as standalone for extreme flood estimations based in short time series.
- Importance of using different estimation methods in order to compare the results.

7. Present research

- Determination of the **temperature** to be considered for event based extreme flood estimations.
- Research on the initial conditions in terms of **soil saturation** and **snow height** to initialize the simulation model for extreme flood estimations.
- **Comparison** between the results arisen from the two main method families (statistics and simulation).
- Determination of the application **limit of PMP maps.**

Acknowledgements
The CRUEX++ project is funded by the Swiss Federal Office of Energy (SFOE)

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Importance of glaciers for CH hydropower

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1. Introduction

- Glaciers = multi-annual storage for hydropower production (HPP)
  - ➢ Delayed discharge from melt: sustained summer flow (Fig. 1,3,4)
  - ➢ Non-renewable source of water during current glacier retreat (since little Ice Age, Fig. 2)

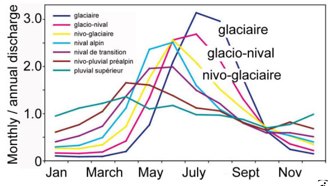

Fig. 1: Selection of Swiss discharge regimes (distribution of monthly discharge throughout the year, see also Santos et al., this volume), *source: OcCC/ProClim Report 2007*

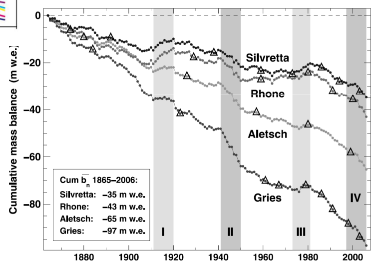

Fig. 2: Time series of cumulative mean specific net balance for Aletsch, Rhone, Gries and Silvretta glaciers for period 1865 – 2006. *source: Huss et al., 2008.*

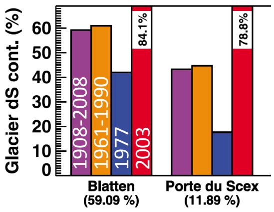

Fig. 3: Estimated relative contribution of glacier storage change to August runoff for the Rhone for 2 different periods and 2 extreme years (in parentheses: glaciation) *source: Huss, 2011*.

- High Alpine HPP designed for max. benefit from glacier-storage
  - e.g. Mauvoisin: 5% of annual HPP from turbining glacier water before inflow into Lake Mauvoisin (Fig. 4)
- Figures on the Swiss-wide role of glaciers for hydropower are missing but prerequisite to understand effect of glacier shrinking
- *Objectives* of this work
  - ➢ Synthesize information on glacier/ice melt and HPP
  - ➢ Quantify future HPP under modified glacier inflows

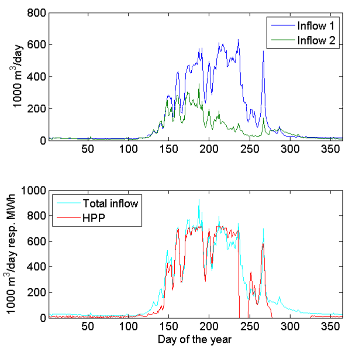

Fig. 4: example of run-of-the-river HPP production at Chanrion (1960 m a.s.l.). Significant flow starts only in June. Inflow 1 comes from catchments with >50% glacier coverage (top). HPP benefits from the delayed flow from inflow 1 (bottom)

2. Sources of information

- Glacier inventories, hydrological Atlas (Fig. 2), SwissTopo
- Observed flow in HPP catchments
- Simulation-based estimates of flows in glacierized catchments (upcoming SCCER-SoE results; see also Fig. 5)
- Estimation of glacier volumes & of volume changes (Fischer et al., 20015, & upcoming SCCER-SoE results)

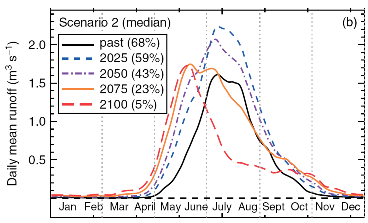

Fig.5: Example of glacier discharge scenarios, extracted from Huss et al., 2008 for the Glacier de Moming, showing the typical pattern with an initial Increase of annual discharge, followed by a significant decrease; sustained summer flows might disappear.

2. Sources of information (2): *HydroGIS*

- Data from HydroGIS (containing 163 HPP schemes with 419 power stations):
  - 25'600 km² (62% of CH area) influenced by HPP (Fig. 6)
  - 99.6 % of Swiss glacier area within HPP catchments (see also Table 1)
  - Mean glacier cover of Swiss HPP catchments: 5.5 %
  - 174 out of 214 HPP reservoirs have glaciers in their catchments

Fig. 6: HPP catchments (light blue) and glacier areas (cyan); *source*: HydroGIS, SwissTopo

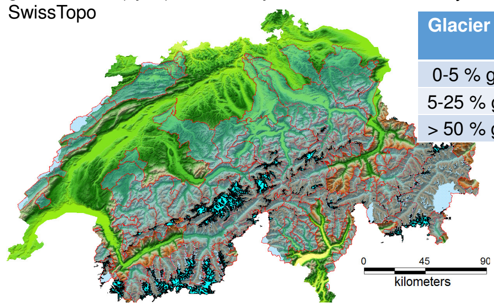

Table 1: glacier cover of the 284 HPP catchments included in HydroGIS (Balmer, 2011)

Glacier cover	# of HPP catchments
0-5 % glacier	76
5-25 % glacier	16
> 50 % glacier	7

3. Some preliminary numbers

- Net glacier mass change corresponds to a few percent of available HPP water resources

Table 2: Specific glacier mass balances estimated by Fischer et al., 2015 for period 1980-2010 for some selected catchments (glacier cover: year 2010); data for Mauvoisin from FMM (years 1988-2000); the melt ratio corresponds to the ratio mass balance / catchment discharge

					Glacier mass balance		
	Catchment	Discharge	Glacierized	Glacierized	mm/year	mm/year	Melt
	area km²	mm/year	area km²	area %	rel. to glacier	entire area	ratio %
Alpenrhein	3213	1129	27.3	0.8	-690	-6	0.5
Reuss	3383	1305	75.7	2.2	-620	-14	1.1
Aare b. Brugg	11665	852	174.5	1.5	-640	-10	1.1
Rhone	5274	1130	569.2	10.8	-590	-64	5.6
Inn	1938	867	46.4	2.4	-810	-19	2.2
Mauvoisin	169	1590	52.6	88.9	-590	-184	11.5
Source	*BAFU*		*Fischer et al., 2015*			*Own calcuations*	

4. Open questions & conclusions

- Glacier volume left in HPP catchments? (Rabenstein et al, this volume)
- Future glacier melt rates? (Farinotti et al., & Peleg et al., this volume)
- Detailed characterization of water intakes influenced by glaciers ?
  - ➢ Decrease of summer production through intake overflow?
  - ➢ Increase of winter water intake ?
  - ⇨ Extension of HydroGIS (Oliva Rodriguez et al., this volume)
- Role of glacier melt water downstream of high Alpine reservoirs?

The synthesis on HPP and glaciers will

- ➢ Monitor the cross-SCCER-SoE progress in quantifying the current/future role of glaciers for Swiss HPP
- ➢ Quantify the potential decrease of HPP under future hydrologic regimes and underline the importance of structural HPP adaptation

References: ***Balmer*, 2012**, Nachhaltigkeitsbezogene Typologisierung der schweizerischen Wasserkraftanlagen, PhD thesis, ETHZ; ***Fatichi et al.*, 2015**, High-resolution distributed analysis of climate and anthropogenic changes on the hydrology of an Alpine catchment, J. Hydrol; ***Fischer et al., 2015***: Surface elevation and mass changes of all Swiss glaciers 1980-2010, Cryosphere; ***Huss*, *2011***, Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe, Water Resour. Res.; **Huss et al., *2008***, Determination of the seasonal mass balance of four Alpine glaciers since 1865, J. Geophys. Res.; ***Huss et al., 2014***, High uncertainty in 21st century runoff projections from glacierized basins, J. Hydrol.

Other SCCER-SoE references: see corresponding contributions contained in this volume.